U.S. National Review of the

International Thermonuclear Experimental Reactor

ITER

Conceptual Design Activity

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SEC. 1. INTRODUCTION

Background

The U.S. Secretary of Energy, Admiral James D. Watkins, U. S. Navy (ret.), recently announced a new policy for fusion development. This policy, which is based in part on the recommendations of the Secretary's Fusion Power Advisory Committee (FPAC) [1], emphasizes the energy mission of fusion and sets the goal of a demonstration reactor (DEMO) in operation about 2025.

Many of the technical foundations for the new policy had been laid earlier in magnetic fusion assessment and planning studies worldwide, including the particularly extensive and detailed U.S. Technical Planning Activity [2]. A broad consensus emerged from these studies regarding the technical issues remaining before a fusion power demonstration. In particular, they all foresaw the need of an Engineering Test Reactor (ETR) to lay the groundwork for construction of a DEMO.

In 1987, the European Community, Japan, the U.S., and the U.S.S.R. initiated the International Thermonuclear Experimental Reactor (ITER) design and R&D activities, combining talents and resources to address the common need for an ETR. The FPAC recommended continuation of U.S. participation in the ITER as an important element of the U.S. fusion program.

The ITER overall objectives were "to demonstrate the scientific and technological feasibility of fusion power" and to "provide the data base in physics and technology necessary for the design and construction of a demonstration fusion reactor." These were expanded in the Programmatic Objectives of the ITER Terms of Reference [3]:

- Plasma Physics Objectives The ITER shall demonstrate controlled ignition and extended burn of deuterium-tritium plasmas, with steady state as an ultimate objective.
- Engineering Objectives The ITER shall validate design concepts and qualify engineering components for a fusion power reactor. In addition, the ITER should demonstrate the reliability of its engineering systems and the maintainability of the reactor. The operation of ITER must demonstrate the potential for safe and environmentally acceptable operation of a power-producing fusion reactor.
- Testing Program The ITER should serve as a test facility for neutronics, blanket modules, tritium production, and advanced plasma technologies. An important objective will be the extraction of high-grade heat from reactor-relevant blanket modules appropriate for the generation of electricity.

These issues -- the physics of ignition and extended or steady-state burn; the engineering and technology of safe, environmentally acceptable, reliable and maintainable reactor systems; and the development and testing of nuclear components, especially breeding blankets -- are not addressable in current facilities, particularly in an integrated manner.

The CDA and the Charge to the National Review

The ITER Terms of Reference also established the following Technical Objectives in support of the Programmatic Objectives:

a) confinement capability sufficient for ignition;
b) inductive pulse-length of at least a few hundred seconds, sufficient for equilibrium burn, with a goal of steady state operation with non-inductive current drive;
c) neutron wall loading of about 1 MW/m^2;
d) useful neutron fluence of about 1 $MW\text{-}y/m^2$, but with the possibility of a neutron fluence of about 3 $MW\text{-}y/m^2$;
e) tritium breeding capability as close to unity as possible without jeopardizing reliability and availability; and
f) overall availability of at least 10% in the technology phase, with availability of 25% during the years of peak reliability.

The four ITER partners have recently completed the three-year Conceptual Design Activities (CDA) phase. The objectives of the CDA phase were to develop a conceptual design meeting the ITER Objectives, to identify the outstanding technical issues, and to prepare an R&D plan addressing these issues. The point design as summarized in the ITER Conceptual Design Report is the culmination of the CDA effort. The four partners are now entering negotiations for the five-year Engineering Design Activities (EDA) phase to produce an engineering design sufficient to support a construction decision about 1996 and to carry out physics and technology R&D in support of the design. Each of the partners is currently reviewing the CDA point design in preparation for embarking on the EDA.

Early in the EDA, the Technical Objectives will be reconsidered by a Special Working Group (SWG) in light of the issues raised during the CDA and the partners' reviews. Under discussion will be the best practical way to achieve the Programmatic Objectives of ITER; whether the Technical Objectives should be reconfirmed or modified; and the degree to which the CDA design represents a point of departure for the EDA.

As reproduced in the Preface, the charge to this U.S. National Review of the ITER-CDA was contained in a letter from Dr. N. Anne Davies of the DOE Office of Fusion Energy (OFE). Briefly, the charge requested a U.S. technical review of the ITER CDA design, to be used in formulating DOE guidance to the U.S. members of the SWG.

As well as reviewing the design, the review committee studied the extensive set of reports prepared as background by the international CDA team, and it heard some forty presentations on the material by U.S. team members during the week of February 11-15, 1991, at Austin, Texas. The Committee thanks the U.S. team members for the thoroughness and quality of their presentations, including the openness and frankness with which they answered questions and discussed unresolved issues.

Finding The ITER-CDA team has done an impressive job, unprecedented in its international scope, in preparing the CDA point design and developing the associated Long Range R&D Plan.

Although the conclusions and findings contained in this Review tend to dwell on those aspects of the design with which the Committee has concerns or takes issue, the Committee also wishes to note the high standard of work that was performed during the ITER CDA. The entire team did an excellent job involving the international tokamak physics community in setting the physics and engineering design guidelines. Showing dedication both to fusion and to international cooperation, the team overcame national and cultural differences in pulling together the confinement data base in a unified and coherent way and in otherwise achieving the CDA objectives. Because of the international nature of the activity, travel requirements often entailed sacrifices by team members and their families. The final engineering design developed during the EDA phase will be possible only because of the team's efforts. In producing a conceptual design of an ETR-class device based on the current or near-term data base and in exploring its implications, the ITER CDA team has rendered an important service to fusion.

Summary of General Conclusions Regarding the EDA

The strong consensus achieved by the Committee in reaching its conclusions was noteworthy. Our conclusions relevant to the Special Working Group are listed below in summary form. They have been derived from considerations detailed in Sec. 2 of the report, where responses to the charge questions are presented.

Readiness to Proceed to the EDA

- The CDA activities have defined a class of tokamak designs to meet the ETR function. The CDA point design appears marginally capable of achieving the ITER objectives, within the uncertainties in the design data base, and a promising direction for further optimization has been identified. An R&D plan has been developed to provide the additional data base required to support a construction decision. We believe that this work is sufficient to justify proceeding to the EDA phase.

ITER Programmatic and Technical Objectives

- The basic Programmatic Objectives "to demonstrate the scientific and technological feasibility of fusion power" and "to provide the data base in physics and technology necessary for the design and construction of a demonstration fusion reactor" should not be altered.

- The machine design should be optimized and the plasma physics objectives should be modified to reflect the following priorities:

    1) a primary objective of achieving the reliable, long-pulse, burning-plasma performance that is required to produce at least 1 MW-y/m^2 neutron fluence during a ten-year testing program; and

    2) the auxiliary objectives of exploring the achievement of ignition and of "steady state" current drive conditions.

- In the formulation of detailed technical objectives, the distinction between the physics and technology phases should be reduced. A single set of technical objectives should be formulated for a single machine. It is important that the primary objective of ITER be identified and the design developed to reach that objective with high probability.

The EDA Activities and Schedule

- The CDA design should be viewed as a point of departure for EDA activities. Before the design is carried to the level of detail associated with an engineering design, an optimization of the ITER conceptual design should be performed with the objective of achieving a design point with more margin of assurance for meeting the testing objectives. This design optimization could be initiated in late 1991, when the central team is in place, and should be completed by mid-to-late 1993.

- The issues of safety and environment (S&E) and of availability, reliability, and maintainability should should have stronger roles in the design (e.g., considerations of S&E should be an important factor in the choice of materials for plasma-facing components; and considerations of remote maintenance, including TF-coil replacement, should be an important factor in the choice of engineering solutions).

- Those R&D activities which pace the schedule and those which address uncertainties affecting the design in critical areas should be initiated as soon as possible. The technology R&D program should give priority to exploring innovative solutions to problems encountered in the CDA design, to techniques enhancing reliability and maintainability, and to techniques enhancing the safety and environmental characteristics of the facility.

- The EDA program should provide sufficient information to support a construction decision by 1996, but completion of the design to enable a start on actual construction would be accomplished during the beginning of the construction phase.

ITER Schedule

- The engineering design and the R&D for all of the ITER systems can be completed within the period 1996-98, consistent with the current ITER schedule.

- The currently estimated ITER physics operational schedule of 6 years is questionable. Even with thorough pre-operation facility preparation, this phase may well take 8-10 years, unless a burning plasma experiment and a steady-state current-drive experiment have successfully operated prior to ITER operations. With this prior experience in hand, the ITER physics phase would be more confirmatory in nature and could be reduced to ~5 years. The technology phase will probably require 10-12 years, as currently planned. In the absence of prior burning plasma and steady-state experiments, a >20-year operation would be needed to achieve the programmatic objectives. Such a long operating time is barely credible technically, and it is inconsistent with the goal of a DEMO in operation by 2025.

EDA Management Organization

- The EDA central team should be organized as a single multinational unit under a strong director who reports to the ITER Council acting as a corporate board of directors. The director should be assisted by appropriate steering/advisory committees.

- Physics R&D is currently "voluntary", based on the assumption that the world tokamak program will provide the necessary data base. This funding basis puts all physics R&D outside the project's control. A mechanism should be put in place to assure that the required research is efficiently organized and completed in a timely manner. In addition, the central team director should have control over some level of funds or credits to support high-leverage physics studies on a priority basis.

- The U.S. home team leader, assisted by appropriate steering/advisory committees, should assign and coordinate home team design and R&D activities, based on DOE concurrence derived from broader fusion program and resource considerations.

- ITER activity oversight and coordination within the DOE-OFE should be carried out through a single project office at the Division Director level. This office should support the central and home teams, assure national program participation in the U.S. home team activities, and generally review and approve the U.S. ITER activity at a policy level.

These conclusions reflect the belief that an ITER aimed at a 2025 DEMO entails a commitment to an energy mission for fusion that must be supplemented by a strong worldwide supporting program. This supporting program must consist of the activities specified in the ITER Long Range R&D Plan, plus a strong base program in each of the parties. In addition, to provide the physics building blocks for extended long-pulse burn, the worldwide plasma physics R&D program should be coordinated to assure, prior to the start of ITER operations, experience in burning plasmas and in steady-state plasmas.

Sec. 2. RESPONSES TO THE CHARGE QUESTIONS

Question 1. "Discuss the relationship of the ITER programmatic objectives to the current U.S. Fusion Program strategy."

Finding The ITER as defined by its Programmatic Objectives would play a central role in a U.S. Fusion Program strategy aimed at a fusion demonstration -- it is responsive to a widely recognized need for a facility of the ETR class; it makes essential contributions to the data bases for the physics of extended nuclear burn and for nuclear and component technologies that are needed for proceeding to the DEMO; it utilizes international cooperation to spread the cost and technical contribution; and it serves as a focus for the domestic U.S. program through the next decade.

Finding The Programmatic Objectives established for the ITER represent a very ambitious step beyond today's facilities. To help assure its success, extensive physics and technology R&D will be required worldwide. To position the U. S. to reap the benefits from ITER success and to continue improvements in the reactor concept, U.S. participation in the ITER and the supporting R&D must, in addition, be part of a more broadly based fusion scientific and technology R&D program.

The DOE policy for fusion development is goal oriented and aimed at a DEMO operating about 2025, as recommended by FPAC and presented to the Congress in the US National Energy Strategy [4]. The DEMO characterization was developed in the INTOR Workshop [5] and in an IAEA Consultants Meeting on DEMO Requirements [6]:

> "The DEMO is a complete electrical power station demonstrating that all technologies required for a prototype commercial reactor work reliably enough to develop sufficient confidence for such commercial reactors to be competitive with other energy sources. The DEMO does not need to be economic itself nor does it have to be full scale reactor size."

The U.S. program leading to the DEMO must then be planned using a rollback approach that determines the issues to be addressed and the facilities required to be ready for that major demonstration.

Employing this rollback approach, the first clear need is a facility providing the essential nuclear testing, component reliability testing, engineering, and safety and environmental data necessary to design the DEMO. The combination required -- moderate neutron fluence, high availability and tritium breeding under integrated, reactor-like conditions -- is unique to and essentially defines the ETR. Within current U.S. program planning, the ITER as characterized by its Programmatic Objectives fills this ETR role.

Planning for a facility, like the ITER, to start operation fifteen years in the future necessarily entails a balance of reach *vs.* risk. As characterized by its Objectives, the ITER represents a very ambitious step from today's operating facilities. This assures its timeliness in the 2020's. However, it also implies that ITER will be a success only if it is supported by effectively focused physics and technology R&D. These efforts must form a bulk of the world fusion program over the next 5-10 years.

To be a strong ITER participant, the U.S. must assume its share of this responsibility. In a coordinated way, the world fusion community must complete the tokamak physics data base, with emphasis on those areas where important operating experience is limited (e.g., burning-plasma physics and steady-state operation) or where special ITER concerns have been identified (e.g., divertor physics under conditions of high heat load, removal of helium "ash", and the avoidance of disruptions). It must develop innovative solutions for the technology requirements that are imposed (e.g., magnets, auxiliary heating systems, breeding blankets, power handling and remote maintenance) and embody these solutions in reactor-relevant components. Finally, the U.S. program must involve its private sector in a meaningful way in all aspects of R&D, design, construction and operation, first for the ITER and later for the DEMO in more of a leadership role.

As also emphasized by the FPAC, deriving full benefit from participation in ITER R&D and from successful ITER operation will require additional, non-ITER-focused R&D that is part of a U.S. domestic base program. To increase the attractiveness of the reactor product from the considerations of safety, environment and economics, the fusion program must continue developments in such areas as confinement concepts and improved materials. These efforts look beyond ITER toward the special demands of the DEMO and the reactor. For example, operation in the second region of stability and use of low-activation materials have not been incorporated into the ITER CDA design, owing to the absence of an adequate current data base. Improvements such as these at the DEMO and reactor stages will be needed to realize fusion's potential to its full extent.

This combination of R&D efforts, one supporting the specific ITER design and the other looking beyond, can only be provided by a healthy and substantial U. S. base program. An inadequate base program would not only jeopardize the ITER success but would also limit the advantages to the U. S. of participating in the ITER.

In the absence of a strong supporting program for the ITER carrying out the required R&D, the ITER Programmatic Objectives would have to be reexamined. Because of the relationship of an ETR to the DEMO, abandoning the ETR objective for the ITER and substituting a smaller technical step now would seriously delay the ultimate goal of the DEMO. Although fewer resources would be required in the near term, owing to reduced supporting R&D, a later ETR would still be required, raising the total cost and postponing the central feature of the Department of Energy's fusion strategy.

Question 2. "Determine the technical adequacy of the ITER point design to meet the programmatic objectives, including necessary modifications to improve the design."

PLASMA PHYSICS OBJECTIVES

"The ITER shall demonstrate controlled ignition and extended burn of deuterium-tritium plasmas, with steady state as an ultimate objective." (Terms of Reference, Annex I, Section 1.1)

Finding From a plasma physics perspective, the CDA reference design goes far toward meeting the ITER extended-pulse-ignition objective. However, important issues have been identified to be resolved in the EDA physics R&D program, including divertor power handling, disruption control and helium ash removal.

Finding The steady-state objective has not been met in a satisfactory way. Conflicting requirements between acceptable current-drive power and divertor-region temperature and heat loads have not been resolved. This issue has been identified as having highest priority for physics R&D during the EDA. Fortunately, however, a larger aspect ratio design option might ease many of these constraints in the current design.

Short-Pulse Ignition Objective (<100 seconds)

Confinement

The present ITER design point is adequate from a confinement viewpoint. In relation to new, improved scalings developed by the ITER team, the design-point plasma reaches ignition with a factor 2 enhancement over L-mode confinement, or equivalently with 75% of ELM-free H-mode confinement, including allowance for the build-up of 10% thermalized helium. In the early stages of ignition, before helium build-up, 25% additional confinement margin is present (equivalent, in the extreme case of no helium, to the addition of about 5 MA of plasma current). Also, if the available heating power were used to drive a slightly sub-ignited plasma burn with the same total fusion power ($Q > 10$), 25% additional confinement margin would also be realized (again equivalent to about 5 MA additional current). On the other hand, the loss of 20% of the energetic alphas would be equivalent to a 15% decrease in confinement.

Without effective helium transport from the plasma core and removal from the edge, the burn would be expected to quench due to helium build up in times of order 100 seconds.

The recent experimental results supporting the ITER empirical scaling laws for confinement suggest a reoptimization of the design point in the direction of larger aspect-ratio. Such a reoptimized design might provide the same confinement capability at reduced plasma current, with correspondingly reduced disruption loads and with significantly improved potential for achieving the extended-pulse and steady-state objectives.

Operational Limits

The ignited-plasma design point in ITER has been constrained to a beta-value below the Troyon stability limit, partly to avoid disruptions, partly because of divertor power-load constraints, and partly because of the absence of control over the current profile. The value of the plasma safety factor has been chosen at the lowest reasonable value consistent with acceptable disruptivity. The plasma density is at, or slightly above, the Greenwald limit. This choice is predicated on recent experimental indications that the edge density, rather than the central density, is the controlling parameter, and that the edge density is limited only by power-handling capabilities in the scrape-off and divertor plasmas. However, the ability to control the density and density profile in the H-mode operation remains uncertain.

Extended Burn Objective (200-2,500 seconds)

Pulse Length

The present ITER design point provides an inductively-driven burn pulse of 200-400 seconds, sufficient to reach saturated helium build-up and require steady-state plasma power-handling, particle exhaust and refueling. The design also provides a "hybrid" inductive/non-inductive operating mode, in which current-drive is used to extend the pulse length to about 2,500 seconds, sufficient to satisfy the minimum requirement of the nuclear-testing program. In this 2,500-second reference extended-pulse mode, the plasma density must be reduced. Therefore, the average neutron wall loading drops somewhat below the minimum value of 1 MW/m^2 required for the testing program. Over a limited outer portion of the surface, the wall load is 1.3 MW/m^2, so that the testing done in this area would be at the minimum required flux. (Note added: the reference hybrid operating mode has not been fully optimized for neutron wall loading, even within the CDA configuration. With optimization, the average and local neutron wall loads are about 20% higher than those in the reference case.)

Power Handling and Particle Exhaust

The design point marginally satisfies the divertor power load constraints for these extended-burn operating modes, but only if special precautions are taken in dispersing the power in the divertor and scrape-off layer. Since the maximum allowable total the power to the divertor plates is about 100 MW under the current design assumptions concerning peaking of the heat load, the long-burn ignited mode of operation requires that about half the alpha-particle power (200 MW) must be radiated. The "hybrid" extended-pulse mode requires that impurities be introduced into the edge plasma, lowering the scrape-off layer temperature and radiating about two-thirds of the combined alpha-particle and current-drive power (300 MW).

It is important to note, however, that the conclusion that large radiated power fractions and separatrix sweeping are required is based on allowance (a factor of 2) for the present range of uncertainties in predicting the width of the ITER scrape-off layer and on a conservative allowance (a factor of 1.7) for power peaking due to expected toroidal and poloidal asymmetries. (An additional engineering safety factor allows for imperfectly positioned tiles, etc.) Further R&D to provide a more accurate basis for predicting the width of the ITER scrape-off layer and to demonstrate methods for reducing toroidal and poloidal asymmetries may reduce the need for such large "physics" safety factors. Reduction of the safety factors would extend the plasma operating space, or it could ease the requirement for separatrix "sweeping" that is part of the present design. The development of improved divertor concepts, either with increased radiative losses from the plasma in the divertor or with improved power-flux limits to the divertor-plate, could be expected also to ease the presently severe design constraints.

The compatibility of the H-mode of confinement with effective helium (and impurity) exhaust is a major area of concern that can only be resolved by further experimental investigations. Effective exhaust of helium requires that the helium confinement time in the core plasma not exceed the energy confinement time by more than a factor of five to ten. Once the helium ions reach the plasma edge, their exhaust into the divertor pumping duct is not expected to pose any particular difficulties. Although experimental data on helium transport in L-mode plasmas indicates that the particle confinement time should be acceptably short, there is as yet little data on helium transport in H-mode plasmas, particularly those with ELM's. At present, the existence of ELM's is assumed in order to prevent the accumulation of helium ash that would otherwise be expected to occur in the H-mode, although the efficacy of ELM's in reducing internally, rather than externally, generated impurities has not been demonstrated. This topic has been assigned high priority in the Physics R&D Plan.

Disruptions

The present design point has taken account of the various consequences of disruptions, to the extent that these have been quantitatively characterized, but these consequences place severe constraints on the design and operation plan. The design makes provision for ECH-driven current near the q=2 surface for active suppression of disruptions. Although the data base for disruption control is lacking, it is anticipated that the use of even partial non-inductive current drive will provide enough control over the current profile to reduce the frequency of disruptions somewhat below the lowest values experienced on present-day tokamaks.

The use of 2,000-second (inductive or hybrid inductive/non-inductive) pulses to meet the requirements of the nuclear testing program, calling for two-week periods of "quasi-continuous" operation and implying a nearly uninterrupted sequence of about 500 successful pulses, imposes stringent demands for low disruptivity. The consequences of a disruption for a test sequence depends on its severity. Because the dwell time between inductive pulse already exceeds the thermal redistribution time in the blanket (regrettably), infrequent short interrupts in the sequence would be manageable (e.g., aborting a few shots to avoid impending disruptions). Severe disruptions requiring cleanup, retuning, etc., would likely require a restart of the test sequence. From this viewpoint, the development of a steady-state operating mode is the preferred approach for meeting the requirements of the testing program. In either case, the development (and incorporation into the ITER design) of active disruption-control techniques has been identified as having high priority for the physics R&D program.

Steady State Operation Objective

Current Drive

The reference current-drive system provides a 19-MA steady-state operating mode in which about 9 MA are produced by neutral-beam current-drive (NBCD), about 4 MA by lower-hybrid current-drive (LHCD) in the outer part of the plasma, and about 6 MA by the bootstrap effect. In this operating mode, the mean plasma density is reduced and the mean temperature raised relative to the ignited operating mode. The understanding of the physics of current drive is sufficiently mature that these extrapolations to ITER are considered credible, although there exists for any of the three components of the non-inductively-driven current only small margin against failure to meet the projections.

Power Handling in Steady-State Operation

Because of its reduced plasma density and increased plasma temperature, the steady-state mode of operation does not satisfy the divertor power-load constraints in the present point design for neutron wall loadings exceeding ~ 0.4 MW/m^2. In particular, for the nominal steady-state reference point at an average neutron wall loading of 0.7 MW/m^2, the heat flux to the divertor plate substantially exceeds the engineering guidelines (still including the physics "safety factor" discussed above), and the elevated scrape-off plasma temperature at the divertor plate leads to unacceptable erosion rates.

Even if a satisfactory solution to the divertor problem could be developed for this reduced-density, steady-state operating mode, the plasma density would remain too low to provide the neutron wall loading required for the testing program.

A reoptimization of the design point in the direction of larger aspect ratio would appear to offer substantial benefits for steady-state operation (in addition to providing a longer inductive pulse). In particular, the plasma current would be lowered (easing current drive requirements), the bootstrap-current fraction would be raised, and the divertor-plate-surface/plasma-volume ratio would be increased. A potential modified design point having an aspect ratio of about four appears to provide a steady-state operating mode satisfying the present divertor constraints and producing an average neutron wall loading slightly exceeding the minimum requirement of 1 MW/m^2. Several design issues specific to these large-aspect-ratio concepts have, however, not yet been fully addressed.

ENGINEERING OBJECTIVES

"The ITER shall validate design concepts and qualify engineering components for a fusion power reactor. In addition, the ITER should demonstrate the reliability of its engineering systems and the maintainability of the reactor. The operation of ITER must demonstrate the potential for safe and environmentally acceptable operation of a power-producing fusion reactor." (ITER Terms of Reference, Annex I, Sec 1.2)

The Engineering Programmatic Objectives

Finding The components of the ITER are on the path towards components that will be used in fusion power reactors. ITER will provide an essential, integrated test of these components. To the extent that ITER accomplishes its availability and fluence goals, it will provide valuable component reliability data.

Relevance of individual components in the ITER point design for the DEMO must be judged as matter of degree. The magnets are essentially of full relevance as they are near full scale of the DEMO, and have high fields, rather typical of current reactor studies. The remote maintenance equipment and methods can also be considered of full relevance. The neutral beam current drive is relevant in the sense that steady-state will be a highly desirable feature of a DEMO, but not fully relevant in falling short of the energy required for a reactor. Alternate current drive techniques (e.g., the ion-cyclotron fast-wave current drive adopted by ARIES) could also be used on ITER, if it is successfully developed on smaller machines.

The blankets chosen for the ITER point design also span a range of relevance. The test blankets would presumably be fully relevant, particularly so if they have the stated goal of incorporating low-activation materials. The driver blankets are relevant in the sense that they use reactor-relevant concepts, and operate the breeding material at relevant temperature, but they have reduced relevance in using a low temperature coolant (to improve safety and reliability, and reduce the need for early development). The heat-flux handling elements identified in the point design have the least relevance. The physics-phase graphite materials have no relevance. The metallic technology-phase components are relevant in concept, but the activation level associated with tungsten would be highly undesirable for a reactor.

Because the ITER firstwall/blanket assemblies, divertor, and test blankets must be remotely replaceable, it will be possible to substitute these components, subject to the constraints imposed by the access to the torus and the significant down times required for major system replacement. For example, a full driver blanket replacement would be expected to require a minimum period of 12 to 18 months. During the EDA, studies of potential up-grades and modifications should be undertaken to more fully develop the required flexibility.

Finding Early integration of safety and environmental (S&E) requirements with other engineering objectives will be necessary if the device is to demonstrate the potential advantages of fusion (e.g., considerations of S&E should play a larger role in determining the choice of materials for plasma-facing components). We concur that use of low-activation materials should be explored as part of the test program.

The graphite divertor that has been chosen for the physics phase plays a dominant role in the safety and environmental aspects of the machine. The use of graphite in this phase, with its large inventory of at-risk tritium, and the use of the high activation tungsten in the engineering phase, are both poor choices from the S&E point of view. The potential for release during a magnet accident (e.g., a ground fault arc from the magnet system to the vacuum vessel) is a typical S&E concern that must be integrated with other engineering choices. See Question 5 for more discussion of the S&E issues.

Finding The reliability of engineering systems and the maintainability of the reactor do not appear to have been given sufficient emphasis during the CDA to assure at this time that ITER can accomplish its reliability and maintainability objectives. The reliability of components and systems required to meet even the minimum fluence goals of ITER are major extrapolations from current operating devices. During the CDA, performance was the principle design driver, rather than the need to achieve a high level of reliability. During the EDA, the choice of design criteria should be reexamined with the view of achieving high reliability.

Structural codes and practices have been developed over many years to guide designers in achieving reliable designs, the Boiler and Pressure Vessel Code (BPVC) being one of the most widely used. The BPVC advises the use of large factors of safety on fatigue (a factor of 2 on stress and 20 on life) to allow margin for uncertainties. Aircraft practice generally calls for a minimum of four on the number of cycles necessary to propagate a crack to the point of element failure, and redundancy to prevent a major propagation of a local crack. The ITER magnets by contrast, in maximizing performance in the minimum envelope, require only a factor of 2 of crack propagation life. This would appear to be at odds with the requirement for life-time reliability.

The R&D programs during the EDA should be optimized to improve the reliability of the ITER components, and to generate a data base related to reliability. However, it will not be possible to establish a fully adequate data base on the reliability of the ITER magnetic systems to provide sufficient confidence to treat the magnetic systems as if they were "permanent" structures. The current data base on operations for the large copper-coil tokamaks, as well as the modest scale superconducting tokamaks, suggests that it will be very difficult to achieve life-time fault-free operation. If the project is to establish the credibility of replacement within a reasonable 2-year window, it will be necessary during the EDA to develop plans for removal of the major magnetic components and to demonstrate the fundamentals of those concepts in R&D programs. Full use of redundancy and spares should also be examined.

The use of an early device-mock-up program in the EDA can have a major impact on the design solutions chosen for ITER. A higher level of priority in the EDA, as well as the use of "best guess" component designs, will be necessary to allow an early start and the time to influence the concepts chosen.

The ability to minimize the number of machine cycles by operating with long pulses, or preferably steady-state, will be an important factor in achieving sufficient reliability. Prediction of the response of complex engineering systems to cyclic fatigue is one of the most difficult challenges for engineering design. Materials tests can form the basis for estimating life-limiting flaws and variations of as-built properties. However, the fewer the required cycles, the less likely components are to fail from fatigue. While the addition of current drive hardware adds complexity and the potential for additional sources of down-time, the increase in reliability in the device core -- more difficult to maintain than external systems -- will lead to a significant net gain.

Finding In one area in particular, the divertor, the technical approach does not appear to be sufficiently robust to offer the necessary reliability, owing to the combination of heat load, particle erosion and disruptions. The lack of a satisfactory solution for the divertor is among the most serious short-comings of the current design. The R&D called for in the physics and technology plans should be addressed aggressively. This will require that the current priorities for machine operations be altered to focus on divertor issues and disruption control, and that a priority for innovative divertor development be established.

The choice of graphite for the physics-phase first wall and divertor reflects past successful experience and the relative tolerance for the anticipated frequency of disruption during the commissioning phase. Because sputtering erosion of graphite materials would not give reasonable component life in the technology phase, even with heavy dependence on the redeposition of material, high-Z metal-coated divertors have been chosen. However, even if such divertors can be operated with low impurity back-flow to the plasma, they are very intolerant to disruptions.

The Engineering Technical Objectives

Many of the ITER Technical Objectives have engineering requirements:

a) inductive pulse-length of at least a few hundred seconds, sufficient for equilibrium burn, with a goal of steady state operation with non-inductive current drive;
b) neutron wall loading of about 1 MW/m^2;
c) useful neutron fluence of about 1 $MW\text{-}y/m^2$, but with the possibility of a neutron fluence of about 3 $MW\text{-}y/m^2$;
d) tritium breeding capability as close to unity as possible without jeopardizing reliability and availability; and
e) overall availability of at least 10% in the technology phase, with availability of 25% during the years of peak reliability.

Finding The ITER CDA design appears to be capable of meeting its Engineering Technical Objectives, particularly if the hybrid mode of operation can be realized, although the margin is small for meeting even the minimum operating conditions required for testing. Fortunately, there appear to be other design points that would provide greater assurance of ITER achieving its testing objectives.

a) Pulse Length

Both available Volt-seconds and the divertor are limiting the pulse lengths in the current design. Although the CDA Volt-second capability is judged to be marginally adequate for the testing mission, small fractional increases would significantly increases the burn time. The best approach, which helps ease both the Volt-second and divertor problems, appears to be a design having a somewhat larger aspect ratio.

Steady-state operation in the ITER point design is limited by the incompatibility between the low density required for efficient current drive and the higher density required for credible divertor operation. The hybrid operation, employing a mix of ohmic drive and 30 percent current drive, is also limited by divertor life. Reoptimization of the design toward a larger aspect ratio holds the promise of removing (at least partially) the impediment to steady-state operation and should be seriously considered during the EDA.

b) Wall loading

The reference hybrid mode in the current point design results in a nominal peak wall loading of 1.3 MW/m^2 at the first wall of the test blanket location. With allowance for the attenuation of the first wall, it is likely that a wall loading of 1.0 MW/m^2 can be achieved at the test blanket, although only over limited areas. However, most of the blanket test modules are embedded through ports and see the full neutron flux, without attentuation by the first wall. Averaged over the entire wall, the neutron loads will be typically half of these values. A larger aspect ratio design could increase the wall loading by about 50 percent.

c) Fluence

Meeting the minimum fluence goals of 1 MW-y/m^2 at the test module will require an average availability of about 10-15 % over a ten-year period, the period now planned for the testing phase. This level of availability seems extremely difficult to achieve from our present vantage point. The ability to run steady-state pulses would have, through the large leverage on reliability, a very large impact on the ability to meet this goal. There must, in addition, be a high premium placed on efficient maintenance of first wall elements.

While ITER is necessary to prepare the data base for the DEMO, it is not sufficient. Even at maximum achievable fluence, ITER can reach only about 10% of the fluence typical of DEMO operation. It will therefore be necessary to use a 14 MeV source, and in-pile fission irradiations, to properly qualify low-activation materials for the DEMO.

d) Breeding Ratio

The point design blanket concepts appear reasonable and compatible with meeting the goal of a breeding ratio approaching unity (0.8-0.9), subject to a more complete analysis of external events such as electromagnetic loading. The choice of reactor-relevant breeder concepts, but with lower temperature coolant, is a reasonable choice balancing reliability and safety while retaining a basically relevant concept.

It is difficult to envision how even the minimum fluence goals for the machine can be met without the driver blanket. Without the blanket, the shipment of the integrated need of $\gtrsim$ 60 kg of tritium (the amount required for a fluence of 1.0 MW-y/m^2) from off-site sources would be required. This would not seem wise if the machine is to demonstrate the safety and environmental advantages of fusion in the public domain. The use of a breeding blanket would reduce the required shipments of tritium by as much as an order of magnitude. Also, the availability of $\gtrsim$ 60 kg of tritium from external sources is highly uncertain.

e) Availability

The demonstration of 25% availability for limited periods in the technology phase is a necessary step to the DEMO, but it is a very large extrapolation from current practice. A combination of aggressive component development and test, conservative structural allowables, efficient remote maintainability, and sustained high-duty-factor operation will be required to meet the availability goals. It is important that more attention be given to each of these factors during the EDA.

THE TESTING PROGRAM

"The ITER should serve as a test facility for neutronics, blanket modules, tritium production, and advanced plasma technologies. An important objective will be the extraction of high-grade heat from reactor-relevant blanket modules appropriate for the generation of electricity." (Terms of Reference, Annex I, Sec. 1.3)

Finding The ITER CDA design appears to be marginally capable of meeting its minimum testing objectives, within the existing uncertainties in the design data base. However, the margin is small. Certain of the operating conditions present difficulties for testing. Fortunately, there appear to be other design points that would provide greater assurance of ITER achieving its testing objectives.

The pulse length of the present 22-MA inductive mode of ITER operation (400 s) is too short to satisfy the nuclear-testing requirements. The design allows a steady-state mode of operation in which a 19-MA plasma current is driven non-inductively by a combination of neutral beams, lower-hybrid waves and the bootstrap effect. However, to achieve an acceptable current-drive efficiency, the plasma density (and hence neutron flux) must be lowered below the minimum value needed for nuclear testing.

A 15-MA "hybrid" mode of operation has also been developed for the technology phase. In this mode of operation, non-inductive current drive (aided by the bootstrap effect) provides a part of the plasma current for pulse lengths exceeding 2,000 secs. As the plasma density must be lowered only slightly, the neutron-flux is marginally adequate for testing. The high-radiation heat dispersal method for the scrape-off layer requires R&D. If the divertor heat flux constraint could be relaxed (i.e., if new data were to allow the safety factors in the design to be reduced), the "hybrid" mode of operation could satisfy the minimum pulse-length and neutron-flux requirements with some margin. For comparisons, the reference parameters for the current "hybrid" mode of operation are given in the following table, together with the minimum and the highly desirable parameters as determined from analyses of nuclear testing needs:

NUCLEAR TESTING REQUIREMENTS

	RECOMMENDATIONS		CDA HYBRID MODE
	Minimum	Desirable	Reference Parameter
Neutron Wall Load (MW/m^2) (peak)	≥1	2	1.3 (partial area)
Plasma Burn Time	> 1000 s	1-3 h to steady state	2500 s
Dwell Time, if pulsed	see text	< 20 s	300 - 400 s
Continuous Test Duration (100% availability)	> 1 week	2 weeks	see text
Neutron Fluence (MW-y/m^2)	1.5	4-6	1.5 (partial area)

(Note added: the reference hybrid operating mode has not been fully optimized for neutron wall loading, even within the CDA configuration. With optimization, the average and local neutron wall loads are about 20% higher than those in the reference case.)

Burn times of the order of 2500 s will be adequate to provide thermal equilibrium for most tests and useful information on tritium behavior. Many tests can be completed in a single burn time. Such burn times will also reduce the total cycles over the machine lifetime to the range of 10^4-10^5 cycles.

The dwell time is, however, a matter of some concern. For dwell times longer than 10-50s, prototypical thermal conditions are lost between burns, complicating interpretation of test data. Unfortunately, it does not appear possible to obtain such short dwell times in any mode of pulsed operation. Pure steady-state operation would be desirable.

Finding Greater R&D effort early in the EDA should be devoted to innovative solutions to high-leverage constraints in the current design (e.g., uncertainties in the divertor behavior requiring conservatism in design, and the limitations in steady-state operation presented by the present aspect ratio).

The modeling uncertainty in the peak divertor heat flux, which limits the ability of the present ITER design to meet the nuclear testing mission, is uncertain by a factor of 3-4. There is also an uncertainty in the prediction of divertor conditions and performance under the range of possible ITER conditions. Improved methods of analysis and experimental data should reduce this uncertainty, permitting a design with a less conservative safety factor.

Preliminary studies indicate the possibility that a larger aspect ratio design (A ~ 4) at the same major radius could more satisfactorily meet the nuclear testing requirements in an inductive mode of operation. This could be superior to the pulsed operation in the present design, depending on the bootstrap fraction and beta-value that can be attained. The larger aspect ratio option requires that current can be "traded" for aspect ratio in the confinement scaling, for which there is recent encouraging experimental data.

Steady-state operation would allow transient-free nuclear testing and could be important in providing the reliability needed for the "continuous" test sequences. A larger aspect ratio design also offers the possibility of an advantageous steady-state mode in which the bootstrap effect provides up to two-thirds of the plasma current, with non-inductive current drive providing the other one-third. Bootstrap currents of this magnitude are predicted to occur in plasmas operating nearer the Troyon beta-limit, especially at larger aspect ratio. Steady state would require the current-drive power to penetrate a large, relatively-high density plasma. However, since the current-drive efficiency is effectively improved by a factor of two by the bootstrap current, the plasma density could be maintained at a level that would provide the required neutron flux.

Finding More emphasis must be placed on obtaining the necessary availability of ITER to ensure meeting its testing mission. Availability goals for the facility, reactor, and their subsystems must be established early in the EDA.

There is substantial concern regarding the achievement of the availability goals required for nuclear testing. The most demanding is the requirement of one-to-two weeks of continuous operation (100% availability), which is very important for component testing. The other goal, achieving > 10% average availability and up to 25% peak availability, is very important for obtaining fluence-dependent materials effects for component reliability testing, and for the use of ITER to test "second generation" blanket concepts within the expected ~10-year testing program. The CDA has not given sufficient attention to the issue of obtaining this level of availability. Availability design goals must be established for the overall ITER system and each of its subsystems/components. The design process must then be driven by these goals and must include reliability analysis and mean-time-to-replace analysis for each subsystem (which was not done adequately in the CDA).

With proper early emphasis on availability goals, reliability as a design driver, and remote maintenance procedures, we believe it is possible to maintain the availability goals for ITER necessary for a viable testing mission. We note that several years of operation will be employed to build up to these availability goals and that many systems (auxiliary systems outside the reactor and some key reactor components, e.g., divertors) must be improved to meet these goals. Achieving a significant availability for the overall ITER system would by itself be an important milestone in fusion energy development, irrespective of the testing mission.

Finding The distinction between the physics and technology phases should be reduced. An operating plan should be developed which acknowledges substantial overlap between physics and technology testing.

As noted elsewhere, unless there is a very aggressive world physics program providing experience in both high-Q-burning and steady-state plasmas prior to the ITER operations, there is concern that the physics phase will last much longer than the nominal projection of six years. This would substantially postpone the technology phase and threaten the achievement of the testing mission's fluence and availability goals because machine-component-life effects would become a factor earlier in the testing phase. One partial solution to this problem, in addition to focussing the physics R&D program to ITER-specific studies, is to minimize the distinction between the physics and technology phases in ITER operation by developing an operating plan that emphasizes the overlap between certain types of engineering/technology testing and physics experiments. A smooth transition from the physics phase to the technology phase is inconsistent with replacing the carbon tiles after the physics phase. A single solution for the PFC components that can serve in both the physics and technology phases is needed.

Question 3. "Identify critical areas in the CDA design where the assumed plasma or hardware performance has a large uncertainty, based on the existing data base, and evaluate the adequacy of anticipated physics and technology R&D achievements, and associated R&D requirements, to reduce these uncertainties during the EDA."

PHYSICS R&D ISSUES

Finding The ITER team has done a commendable job in mobilizing the international fusion physics community to identify the R&D needs of the present CDA design and the machines where they can be addressed. The Physics R&D requirements, while thoughtfully developed and comprehensively covering all identified needs, are somewhat lacking in specific technical requirements and dates by which results are needed. The Physics R&D requirements should be reformulated to more clearly identify specific technical tasks and required completion dates.

Finding Because the Physics R&D Plan comprises voluntary responses to the R&D requirements, it lacks cohesive organization and it may not be fully dependable. The physics R&D contributions should be organized into an effective plan, possibly through task-oriented working groups. Arrangements should be made to assure that work is done in a timely manner, and funding paths should be developed to ensure that effort is applied to certain tasks that are not likely to be adequately addressed in a voluntary program.

The ITER program places high reliance on, and can be expected to benefit substantially from, the proposed Physics R&D program. This program should be supported, and effective means should be identified to organize a worldwide response. The present plan is a compendium of voluntary responses from the fusion laboratories of the four partners to the stated ITER physics needs. The voluntary nature of these responses leads to considerable uncertainty in the completeness and timeliness of the results. There is no mechanism by which to provide greater support in areas represented only weakly in the voluntary plan or to minimize redundancy in well-supported areas. The ITER Team should sharpen their present detailed statement of Physics R&D needs to contain more explicit statements of the technical requirements, relative priorities, and the needed dates. The four partners should then establish a mechanism to respond to these needs with a plan for satisfying these needs, along with a mechanism for assuring completion of the planned work.

The areas of disruptions, of long pulse operation, and of divertor operation with long pulse lead the issues for physics R&D. They, particularly, would benefit from more explicit descriptions of needed work.

The R&D program should give greater emphasis to innovative solutions to troublesome design problems. Clearly, working within the bounds of present day technology has not resulted in acceptable solutions in some areas. New solutions to these design problems should be encouraged.

ISSUE: The projected impact of disruptions on both the design and on operational availability is high.

DISCUSSION: The ITER Team has identified the areas in which disruptions impact the design. Plasma disruptions impose high electromagnetic loads on in-vessel components. Disruptions also produce high localized heat and particle loads on the plasma-facing components. These high loads are a concern not only because of the instantaneous damage that can potentially be produced, but especially because of the long term erosion effects that would severely reduce availability during the technology phase. Particular concern exists that the disruptions seen in some tokamaks can produce high currents of very-high-energy runaway electrons. These have the potential to substantially damage material behind the first wall. The occurrence of a disruption terminates a discharge and thus could strongly effect plasma availability during the technology phase, unless the frequency is maintained at a very low level. Disruptions are seen in all major tokamaks and, while some research has been done to characterize and avoid them, they are often treated as operational issues which are not pursued once conditions are achieved in which their impact on the research program is acceptable. Research efforts directed toward disruption control have generally suffered from lack of suitable tools (e.g. lack of high power rf heating and current drive systems). The ITER design has not yet made full use of the information that is available. In particular, the data available on vertical displacement events has not been incorporated into the engineering design.

ADEQUACY OF PROPOSED R&D: The Physics R&D Program establishes a detailed plan with a specific schedule. Responses from a number of tokamaks are required to characterize and model disruptions. The resources to accomplish this are in place, but more run-time must be devoted to this topic in a timely manner. In addition, the existing data base from a number of tokamaks may already be adequate for a study of the extent to which repetitive operation at fixed conditions can reduce disruptivity to acceptable levels. The active control of disruptions is a more demanding task. Effective means must first be identified to anticipate the onset of disruptions (this can be now done for some, but not all, disruptions). Effective techniques, such as profile control, must be developed to control them.

ISSUE: Understanding of the heat loads to the divertor is crucial to achieving an acceptable design.

DISCUSSION: The development of divertor designs for ITER that can effectively handle the anticipated high heat flux has been given substantial attention. The designs developed are marginal because of the high heat loads, because of the peaking of the heat flux, and because of the uncertainties in both. The uncertainties have required designers to adopt large "safety factors", typically in the range 3-4. It is likely that these designs could be improved by a better understanding of the heat loading and the development of techniques to reduce both the actual heat loads and their uncertainties. This issue becomes critical in the regimes required for long-pulse current drive, where the low densities required for efficient current drive lead to high edge temperatures and unacceptable erosion rates at the divertor plate.

ADEQUACY OF PROPOSED R&D: Productive programs are in place in a substantial number of facilities worldwide and a detailed program has been developed as part of the voluntary physics R&D plan. However, the plan does not give sufficient emphasis to the need to find a self-consistent solution to the problem of current drive in divertor discharges. The importance of these tasks clearly warrants establishing an explicit schedule by the ITER team and placing high priority on these tasks by existing facilities. Particular emphasis should be given to establishing effective edge plasma diagnostics and developing effective models. In addition, the ITER-EDA should take the lead in advocating development of advanced divertors.

ISSUE: Adequate helium and impurity particle transport from the core plasma is required to prevent helium buildup from severely degrading thermonuclear performance.
DISCUSSION: Helium buildup in the core plasma would substantially degrade plasma performance. Helium removal can only be achieved by achieving adequate transport through the plasma to the edge boundary layer, and then removing it by pumping. Evidence exists, but with considerable uncertainty, that helium transport through H-mode discharges is poor and that the rate is a function of the ELM frequency in the H-mode discharge.
ADEQUACY OF PROPOSED R&D: The ITER R&D program sets out a plan to address this issue. Addressing this issue in present day devices is difficult, but not impossible, due to the difficulty of both sourcing helium deep in the plasma and removing it from the edge. Experiments using helium-loaded pellets or beams for deep implantation have been proposed and should yield valuable information.

ISSUE: Theoretically predicted alpha particle instabilities could result in serious loss of confinement.
DISCUSSION: Alpha particle instabilities have been predicted theoretically to cause prompt loss of energetic alpha-particles. Calculations also show that these losses would have to be particularly severe in order to cause a substantial confinement degradation. These instabilities can only be observed in devices producing D-T thermonuclear reactions. Present day experiments can observe these effects using beams of energetic ions, but the required parameters occur only near the limits of the machine operating regimes. Preliminary evidence for the existence of these modes has been seen in these experiments, but loss rates have yet to be determined.
ADEQUACY OF PROPOSED R&D: The ITER Physics R&D program addresses these issues. Progress should be encouraged in existing machines, not withstanding the limited operating space available. DT experiments in TFTR and JET should provide important low-Q data, albeit at a later date.

ISSUE: Better understanding of the scaling of confinement with aspect ratio should allow ITER to establish a more attractive design point.
DISCUSSION: The present design of ITER was optimized for an aspect ratio of ~ 3, appropriately because virtually all of the available data during the formative stage of the design was near this aspect ratio. More recent data is beginning to indicate a positive scaling of confinement with aspect ratio. Furthermore, preliminary design studies indicate that increasing the aspect ratio could benefit the design substantially. Because a change in the design point is only practical early in the design, the relevant research must be carried out promptly.
ADEQUACY OF PROPOSED R&D: The U.S. ITER team has extensively studied this option at the system-code level of detail. The Physics R&D plan identifies the clarification of the aspect ratio (A) dependence of confinement to be an important issue. A number of operating experiments can provide modest contributions. A very valuable input is expected from the JT-60U device (A~4).

ISSUE: Efficient current drive techniques are required to drive all or part of the plasma current, and also to control plasma profiles.

DISCUSSION: The ability to drive plasma currents non-inductively using neutral beams (NBCD) and a variety of rf waves has been established, along with the existence of an additional contribution from the bootstrap current. The data base is best developed for NBCD, due to the widespread availability of high power beam systems. However, the required injected beam speed in ITER would exceed the Alfven speed, placing the plasma in a new physics regime and raising concerns that NBCD efficiencies seen in the past are not representative of ITER conditions. The progress of ion-cyclotron current drive, which offers some potential advantages when applied to ITER, has been limited by poor efficiencies observed in some experiments and by inadequate power in others.

ADEQUACY OF PROPOSED R&D: The Physics R&D plan is appropriate here. The major needs will be adequate experimental attention on devices having neutral beam injection with significant tangential components and adequate suitably powered experiments evaluating the potential of rf current drive. More studies of the dependence of the bootstrap current on plasma parameters and profiles are also needed.

TECHNOLOGY R&D ISSUES

Finding The Technology R&D Plan identifies the R&D needed to support the present CDA design, and it would likely be applicable to similar technical approaches applied to changes in the design. The R&D program should include more research into innovative solutions in areas where the present design concepts are marginal.

Finding The existing Technology R&D plan has been developed in considerable detail. It depends heavily on existing base programs remaining in place. It does not adequately include diagnostics, reliability, safety, and environmental issues and should be expanded to include specifically these neglected important areas.

ISSUE: Divertor design requirements place several demands on the materials of plasma-facing components, and the characteristics of the candidate materials are uncertain. The development of new materials with improved properties could greatly benefit ITER.

DISCUSSION: It appears that there might be little or no safety factor between material design limits and the ITER divertor design parameters. For carbon or carbon composites, adequate lifetime depends on the redeposition of material to reduce, by large factors, life-limiting erosion. The material properties of the divertor tiles after substantial redeposition are uncertain. The thermo-mechanical behavior of the design approach (cooling pipes brazed to tile blocks) after many cycles is uncertain, and the likelihood of premature failure is not known. For high Z or other materials, impurity release into the plasma is uncertain, but the presence of such high Z materials in tokamak discharges has been seen to lead to serious degradation.

ADEQUACY OF PROPOSED R&D: The planned R&D focuses on developing and testing various first wall and divertor plate armor materials and techniques, with some effort on advanced concepts. The materials development and testing (in existing facilities) plan is adequate, but an advanced test facility needs much better definition. The advanced facility would more realistically gather data at the requisite heat flux and under simulated ITER conditions and study the processes of erosion and redeposition. The cost of such a facility, if one can be conceptualized, is probably much higher than is included in the R&D plan. However, it will be very difficult to simulate the real tokamak environment with a simplified test stand, particularly since disruptions play a major role in determining the lifetime. Additionally, for high-Z metal plates, the issue is impurity accumulation in the tokamak, so tests in diverted tokamaks are also essential. We note that JET-U and JT-60U will have heat flux values near those that are at a safe limit for ITER (~15 MW/m^2), and that testing in those machines would give the most valuable data base for ITER, although they lack the ability to study erosion/redeposition.

ISSUE: Negative-ion neutral-beam technology is at an early stage of development, and there are significant issues to be resolved in both research and development. The timescale for the R&D plan is very short, and this increases the risk of the plan.

DISCUSSION: Negative ion beams will be highly desirable in ITER owing to their high current drive efficiency, which minimizes the required power and lowers the divertor heat loads. The technology for the high required beam energy is immature, raising concerns that the goals cannot be achieved. However, both volume and surface sources have a long history of development and are close to achieving the required current density, divergence and other needed parameters. The accelerator technology must be demonstrated using these sources, as here also there are significant issues like breakdown with each of the proposed approaches, electrostatic and electrostatic quadrupole.

ADEQUACY OF PROPOSED R&D: The R&D plan presented is ambitious (partly in its timescale) and success oriented, but with minor modifications it could support an ITER construction decision by 1996. A recent ISCUS review committee concluded that "the greatest technical uncertainty is not with the construction of the hardware or operation of the test facilities, but with the fundamental physics effects of accelerating an ampere or more of high quality negative ions to 1.3 Mev for multi-second pulses." To minimize the risk, it is essential to continue developing sources of several kind, as the plan proposes. To further reduce risk, it is essential to carry both ES and ESQ accelerator concepts to a common performance goal of a 1.3 MeV, 1 A, 2 s H^- beam. This differs from the present plan which has different performance goals for the ES and ESQ accelerators. This demonstration at the end of 3 years (as shown in the plan) should be one of two major milestones in the R&D plan. The other, on the same time scale, is to show that a suitable 1 A source can be run for long pulses (two-weeks was recommended by the community). To achieve these goals on this time scale will require high funding levels starting the first year to prepare the required facilities, and will require a high degree of focus and coordination among the partners in this R&D effort.

ISSUE: Component reliability is uncertain in a number of critical areas.

DISCUSSION: ITER will require a high availability compared to the current large experimental devices. This will be especially true for the 1-2 week "quasi-continuous" test periods. A normal "plan" for a specified availability is formulated by initially allocating availability quotas to each subsystem (here to include the plasma) and assessing the factors that make up the availability for those individual systems. Assuming their independence, the product of those availabilities give the availability of ITER. The individual factors are arrived at by fault analysis to determine the time-to-failure, and by the repair schemes to determine the time-to-repair. Factors such as the required level of QA, the plans for spare parts, the addition of more maintenance equipment, the incorporation of design features to more readily permit repair, etc., are all required elements of the plan. Several iterations and adjustments of sub-system quotas may be needed to finalize the plan.

ADEQUACY OF PROPOSED R&D: The R&D plans are generally inadequate in this regard. They emphasize rather the ability to achieve the required specifications of performance. This failing is acute in systems with long time-to-repair, such as the TF magnets or the driver blanket. It is also acute in immature systems like negative ion beams which, owing to our lack of experience, may require many spare parts to cover the possible failures in components with unknown failure rates. Divertor tiles fall in the same category, since projections of replacement frequency range widely. While the inadequacy of an availability plan is widespread, its impact is most important in a limited number of areas. The R&D in those areas should be reviewed in this context.

ISSUE: The Technology R&D Plan is insufficiency responsive to safety issues identified in the safety assessment carried out by ITER's CDA phase.

DISCUSSION: Various safety and environmental (S&E) features of ITER were assessed in the CDA phase, but S&E acceptance attractiveness did not play a strong role in the design process. S&E goals relating to reactor accidents, routine exposures and emissions, and radioactive wastes should now become part of the design process. The setting of these goals should be reasonable and not be such as to eliminate all possible choices. Iteration between design engineers and the safety members of the team will be required in agreeing on goals and in developing the design.

ADEQUACY OF PROPOSED R&D: In the absence of a specific safety R&D plan, S&E issues need to be suitably embedded into the Physics and Technology R&D Plans. We find that the Physics R&D Plan is already satisfactory in this respect, but that the Technology R&D Plan needs improvement. (See also the discussion under Question 5.)

ISSUE: The engineering design of the diagnostic system is incomplete, and the current reference design is inconsistent with the physical implementation of many of the diagnostics.

DISCUSSION: Diagnostics strongly couple to machine design, and this will be even more true in ITER because the components must be radiation hardened, pass through obstructive shields, and permit remote maintenance. To generate an appropriate R&D plan the machine design, including its diagnostics, must first be done in a consistent and compatible way.

ADEQUACY OF PROPOSED R&D: In the R&D plan, emphasis is placed on radiation effects on components and new diagnostics appropriate to the different environment (plasma regimes, fusion products) ITER represents. Insufficient attention was given to the overall system and its optimization in this difficult environment. Also, the incorporation of elements in the R&D plan that will arise from constraints and considerations of machine design and maintenance is lacking.

Question 4 "Determine the technical adequacy of the proposed experimental and testing program during ITER operations to accomplish the ITER objectives, and identify the new physics and technology information that ITER would contribute to the development of fusion reactors."

Finding If ITER operates at the upper ranges of its technical objectives (high-Q or ignited steady-state operation, neutron wall load $\gtrsim$ 1 MW/m^2, neutron fluence ~ 2-3 MW-y/m^2, availability ~ 25%), it will provide the contribution to the DEMO data base required of an integrated engineering test reactor (ETR). If ITER operates in the lower range of its technical objectives (high Q or ignited long-pulse operation, wall load ~ 1 MW/m^2, neutron fluence ~ 1 MW-y/m^2, availability ~ 10%), it marginally will provide the ETR support for the DEMO, but the extrapolation to the DEMO in fluence would be uncomfortably large. In both of these cases, no further major ETR class device will be needed prior to the DEMO, although facilities for optimizing the tokamak, for materials testing, and for component development will be required to complement the data base provided by ITER. If ITER realizes a performance level significantly below its technical objectives (short-pulse operation, neutron wall load < 1 MW/m^2, neutron fluence < 1 MW-y/m^2, availability < 10%), another major ETR class device will be necessary prior to the DEMO.

Finding The contribution of ITER to the physics data base required for the DEMO will be substantial. The six years presently planned for the physics phase may have to be extended by 2-4 years, unless the successful operation of a burning plasma experiment and a steady-state current-drive experiment precedes ITER operation. In this case it may be possible to shorten the physics and commissioning phase to about five years.

The ITER Programmatic Objectives are "to demonstrate the scientific and technological feasibility of fusion power" and "provide the data base in physics and technology necessary for the design and construction of a demonstration fusion reactor." We take these statements as a point of departure for responding to this question. We first define the characteristics of a "demonstration fusion plant" (DEMO), then identify the data base that is required for its design and construction, from which we then identify the contribution to that data base that must be made by ITER and the contribution that must be made by other facilities. By comparing the ITER testing objectives and capabilities with this required contribution and by considering the proposed operating schedule, we can develop a response to this question.

Definition and Date Base Required for a DEMO

There have been many studies aimed at defining the characteristics of a DEMO. The views of the US, USSR, Japan and the EC were discussed during the course of the INTOR Workshop [5] in the early 1980's and in an IAEA Consultants Meeting on DEMO Requirements [6] in 1986, during which a common view emerged.

The IAEA Consultants Meeting [6] provided a concise definition of a DEMO.

> "The DEMO is a complete electrical power station demonstrating that all technologies required for a prototype commercial reactor work reliably enough to develop sufficient confidence for such commercial reactors to be competitive with other energy sources. The DEMO does not need to be economic itself nor does it have to be full scale reactor size."

We note that this definition focuses on the economic features of the DEMO. In our view, its safety and environmentally features will be equally important.

This IAEA Consultants Meeting [6] also provided a set of objectives which were consistent with those identified in previous studies. These DEMO objectives are:

a) production of several hundred megawatts of electricity and achievement of net electrical power production;
b) production of tritium in the blanket, with a net breeding ratio greater than unity;
c) demonstration of the development and integration of large-scale components which can be extrapolated to a commercial reactor;
d) demonstration of component, systems and plant reliability, availability and lifetime at a level that would be acceptable for a commercial reactor;
e) demonstration of a safe and environmentally acceptable fusion reactor operation that would satisfy the requirements for a commercial reactor; and
f) demonstration of commercial feasibility (although the DEMO would not need to be itself economically competitive).

We take this definition and these objectives for a DEMO as a starting point for defining the role of ITER in magnetic fusion development, incorporating further the opinion expressed in many studies [e.g. 5,6] that items d) and f) require lifetimes of 10-20 $MW-y/m^2$, neutron wall loads of ~ 2-4 MW/m^2 and availabilities $\gtrsim 50\%$. A commercial reactor is expected to have somewhat higher values of these parameters.

Prior to the construction of a DEMO that would have an acceptable probability of accomplishing the above objectives, it will be necessary to accomplish certain DEMO prerequisites, which when successfully completed would establish the data base required for the design and construction of a DEMO:

a) demonstrate long pulse, high-Q or ignited, controlled D-T plasma operation;
b) develop and test improvements in the toroidal confinement concept;
c) develop and test fusion reactor components and systems that extrapolate to a commercial reactor;
d) integrate reactor relevant components into a fusion reactor system and test reliability of components and interfaces in this environment to some significant fraction of the anticipated DEMO lifetime and availability;
e) develop and test remote maintenance technology for a fusion reactor;
f) develop and test materials which can perform satisfactorily under fusion reactor power flux and irradiation conditions; and
g) develop and tes· ··sign features and materials which will enhance the safety and environmental a· ·ptability of a fusion reactor.

Facilities Required to Provide the DEMO Data Base

We will now consider each of these DEMO prerequisites, in turn, and examine the roles that could be played in their accomplishment by plasma physics experiments, by component and systems test facilities, by 14 Mev neutron materials irradiation facilities, and by an integrated engineering test reactor such as ITER.

Prerequisite a) could be accomplished in one or more long-pulse D-T plasma experiments which do not address the engineering testing DEMO prerequisites, or in ITER, or in a combination of the two. If ITER is necessary to accomplish the engineering testing prerequisites, which we believe to be the case, then this prerequisite a) would perforce be accomplished in ITER. However, prior experience in separate short-pulse, D-T-burning and long-pulse, non-burning plasma physics experiments would increase confidence that the subsequent ITER would accomplish its total objectives.

Prerequisite b) could be accomplished in plasma physics experiments designed specifically for that purpose. Optimization of the configuration, investigation of the second-stability regime and optimization of the bootstrap current are among the vital physics tasks not addressed by ITER.

Much of prerequisite c) could be accomplished in component test facilities and, in the case of plasma facing components, in plasma physics experiments designed for that purpose. However, the testing of components and systems in a fusion reactor irradiation (including heating) environment, which is particularly critical for the blanket, can only be accomplished in ITER or in a fusion irradiation device (e.g. a small, highly-driven fusion device).

Prerequisite d) could only be accomplished in ITER.

Prerequisite e) will require test facilities, but a convincing test could only be performed by ITER.

A small volume, very high flux neutron source (e.g., accelerator or mirror-machine based) could irradiate small samples ($\leq$ liter volume) to dpa (displacements per atom) levels corresponding to the anticipated DEMO lifetime (10-20 MW-y/m^2), which would be a vital contribution to prerequisite f) and g). Fission reactor irradiations could contribute to f) by providing for larger samples, at lower flux, but would still not provide for component irradiation and would not exhibit the correct fusion reactor neutron spectrum. However, prerequisite f) also requires large volume (~ m^3) component irradiation in a fusion reactor radiation environment to some significant fraction of the anticipated DEMO dpa-levels, which could only be accomplished in ITER or a fusion irradiation device.

Prerequisite g) will require test facilities, but an integrated test in ITER would provide much greater confidence.

Based upon the above considerations, we believe that the DEMO prerequisites could be accomplished by the following combination of facilities.

a) ITER which would accomplish DEMO prerequisites a) and d) and which would contribute essentially towards prerequisites c), e), f) and g);
b) plasma experiments which would accomplish DEMO prerequisite b) and would support the accomplishment of prerequisite a);
c) component and system test facilities which would contribute to accomplishment of DEMO prerequisites c), e) and g); and
d) fission reactors and a small volume, high flux "14-Mev" neutron source that contribute to accomplishment of DEMO prerequisites f) and g). (A fusion irradiation device could also contribute to prerequisites f) and g).)

This strategy for accomplishing the prerequisites for the construction of a DEMO features an ITER which integrates plasma physics and reactor relevant technologies into an integrated test facility that accomplishes or contributes to the accomplishment of many of the DEMO prerequisites.

New Physics Information Provided by ITER

Short Pulse (≲ 100s) High-Q or Ignited Operation

During short-pulse D-T operation, ITER will provide new information in several areas of physics:
- confinement properties of DEMO-size plasmas;
- alpha-particle transport effects, orbit loss and collective modes (e.g. TAE, sawtooth);
- characteristics of alpha heating(e.g., profile evolution and overall heating efficiency);
- test of high-recycling divertors without ash removal;

A short-pulse burning-plasma experiment could contribute prior information on most of these topics.

Long-Pulse (200-400 s) Burn

During longer-pulse D-T operation, ITER will provide additional physics information:
- fueling and ash removal;
- efficacy of a high recycling divertor;
- feasibility of the high-T, low-n regime needed for steady-state operation;
- disruption avoidance/control in a D-T plasma; and
- burn control in extended pulses.

Most of these topics go beyond what could be learned in a short-pulse burning-plasma experiment.

Extended Pulse (> 2000s to steady-state) Operation

During the extended pulse phase of D-T operation, ITER will provide additional information on the following:
- evolution and control of the current profile in a burning plasma;
- efficacy of current drive and bootstrap current for pulse length extension and steady-state;
- fueling, impurity accumulation and ash removal; and
- edge-plasma and divertor behavior.

A non-D-T steady-state experiment could contribute prior information on many of these topics.

Definition of Technology Testing Requirements for ITER

The definition of testing requirements for an engineering test reactor has been the subject of extensive analysis over the past decade (e.g. [5,7,8]) and most recently by the ITER team [9].

Nuclear Testing

The nuclear testing program of ITER will be accomplished by means of experiments on a number of nuclear components, including blanket test modules which will be introduced into ITER in its technology-testing phase, as well as on the breeding blanket installed on ITER. Unlike the basic breeding blanket, the test modules will allow the use of advanced (e.g., low activation) materials as well as conventional materials, and will include advanced blanket concepts for breeding and electricity generation. The nuclear testing program of ITER is intended to provide a powerful, albeit partial, demonstration of the ultimate potential of a fusion blanket [9].

ITER must achieve a minimum neutron power load of 1 MW/m^2 at the test module, which requires a somewhat larger minimum neutron load at the first wall (wall load), perhaps as high as 1.5 MW/m^2 depending on the design of the first wall and the location of the test modules, in order to accomplish the nuclear testing mission. The required value of the neutron wall load is determined by two factors: 1) engineering scaling requirements on the heat source to obtain meaningful test information, and 2) fluence requirements. Studies on engineering scaling for nuclear components indicate that the wall load should not be scaled down more than a factor of 2-3 compared to DEMO in order to preserve key nuclear phenomena [8]. For a fluence requirement of 2-3 MW-y/m^2, a neutron wall load of $\gtrsim$ 1MW/m^2 is required to keep the required availability below 30% for 10 year operation.

The nuclear testing program will impose other requirements on plasma performance, especially in relation to pulse length and duty factor. The minimum pulse length and maximum dwell time (interval between pulses) may be derived from the characteristic time constants in representative blankets, which range from a few seconds to several hours. The minimum acceptable value of pulse length (> 1,000 secs) is derived from the time constants for thermal conduction and bulk temperature rise in a solid breeder, which range from 100 to 1,000 seconds. The desirable value of pulse length (> 1 hour) would allow steady-state conditions to be approached in regard to tritium release and surface absorption and diffusion of tritium in a solid breeder, for which the time constants are in the range of an hour, depending on breeder temperature. In either case, an essential requirement of the testing program will be for "continuous" tests, involving uninterrupted sequences of pulses interspersed by the minimum possible dwell times (< 200 s manageable, but < 20 s desirable). The duration of a "continuous" test (1-4 weeks) is derived from the characteristic time constants associated with approaching a steady-state inventory of tritium in a solid breeder and with diffusion of tritium through structural materials for both liquid-metal and solid breeders [8,9].

There is a substantial incentive for ITER to achieve a level of performance that corresponds to a peak first-wall fluence of 2-3 MW-y/m^2 in order to achieve the nuclear testing mission. The fluence requirement of 2-3 MW-y/m^2 is derived from the results of several studies that show: 1) the maximum fluence received at the test module is a factor of 1.5 to 2 lower than the wall lifetime fluence (owing to neutron attenuation in the first wall and also the need for sequential sub-module to module testing), 2) credible concept verification requires attainment of fluence within a factor of ~ 3 of DEMO, 3) numerous individual effects and sub-component interactions are observed at such fluences (e.g. breeder burnup effects, breeder/clad interactions, breeder/multiplier swelling, helium embrittlement), and 4) many tests requiring several periods of continuous operation, each period is ~ 1-4 weeks; the test matrix to be performed requires 5-10 such periods per year for ~ 10 years [9].

Large Volume Materials Testing

Several recent studies [e.g. 10], including one by the ITER team [9], have concluded that the materials irradiation data that could be obtained in a large-volume, low-fluence, fusion neutron environment like ITER would provide an essential supplement to the small-sample, high-fluence materials irradiation data that could be obtained in a neutron source and to the data that could be obtained in fission reactors.

The value of materials irradiation data from ITER is directly related to the dpa, which can be related to the fluence at the test site by 10 dpa ~ 1 MW-y/m^2. Below 1 dpa, only initial changes in materials properties would be seen. Between 1 and 10 dpa, several new phenomena would be seen: loss of ductility and change of strength in metals, creep relaxation, helium embrittlement, and swelling in graphite and ceramics. Between 10-50 dpa, several additional new phenomena would be seen: lifetime limits in graphite, saturation of mechanical property changes in metals, swelling in FCC metals, "burn-up" effects in solid breeders, creep-swelling interactions and irradiation "aging" effects such as accelerated grain growth. Above 50 dpa, end-of-life effects in standard alloys, swelling in advanced alloys and high helium concentration effects would be seen. Thus, there are three dpa "thresholds" for entering regimes in which new phenomena would be observed at roughly 1, 10 and 50 dpa, corresponding to 0.1, 1.0 and 5.0 MW-y/m^2 at the test site [8].

The average neutron fluence in the test sample would be reduced by ~ 1/2 relative to the first wall fluence. Thus, the three dpa thresholds correspond to fluences at the first wall of ~ 0.2, 2.0 and 10.0 MW-y/m^2.

We consider the attainment of 10 MW-y/m^2 in ITER to be unrealistic. From the above considerations, we find that there is a significant incentive to achieve dpa levels in excess of 10 at the test site, and hence to achieve peak first-wall neutron fluences of at least 2-3 MW-y/m^2.

Component Reliability Testing

A study [10] was performed in the INTOR Workshop to determine how long a component must be operated in INTOR (≈ITER) in order to provide a given level of confidence that a similar component would perform satisfactorily to its mean-time-to-failure (MTTF) in a subsequent DEMO. A "sufficient" level of confidence was defined to require a test time in INTOR of 3.5 times the MTTF of a similar component in a DEMO. The minimum operating time to obtain any significant information of this type was several thousand hours. Significant information on the TF and PF coil systems required about 20,000 hours of operating time, and significant information on the divertor and vacuum system required about 28,000 hours. This study found a substantial incentive to operate for 20,000 - 30,000 hours, which, for ITER with a neutron wall load of ~ 1 MW/m^2, corresponds to a first-wall neutron fluence of roughly 2-3 MW-y/m^2.

New Technology Information Provided by ITER

ITER will develop and test fusion reactor components and systems that extrapolate to a commercial reactor. Most of these items do not contain all the features of commercial reactor components (such as advanced low-activation ceramic composite materials), but they have various reactor relevant features. The superconducting magnet and remote handling systems are likely to be among the most reactor relevant systems. The power handling systems (first wall and divertor) have perhaps reactor relevant structural arrangements, cooling methods, etc., but advanced materials are expected to be developed for reactor applications. These are probably the least reactor-relevant systems. The breeding blanket uses some reactor-relevant features, and the test blankets have a great deal more.

Many auxiliary systems on ITER will extrapolate to a commercial reactor. Again materials may differ. Fueling devices, fuel processing, vacuum pumps and hardware, NBI and ECH systems, control diagnostics are all potential reactor relevant systems that will be tested on

ITER. However, it should be noted that the type of NBI systems being developed for ITER do not appear to extrapolate to the energies needed for power reactors.

The ITER test program will integrate reactor relevant components into a fusion reactor system and test reliability of components and interfaces in this environment to a significant fraction of the anticipated DEMO lifetime and availability. The fluence on ITER is a key to reaching a "significant" fraction of DEMO lifetime in a test. The anticipated fluence on DEMO is 10-20 MW-y/m^2. A fluence of 3 MW-y/m^2 on ITER is a much more significant fraction of the DEMO fluence than the ~ 1 MW-y/m^2 objective of the CDA design. Increasing this fluence is important in meeting the testing needs of DEMO.

ITER will be a convincing test of reactor relevant remote maintenance technology. The arrangement of the tokamak in part defines the requirements for the remote maintenance equipment, but the details of the equipment are not expected to be critical in this integrated long-time test. The ITER experience will provide time-to-repair data on reactor-relevant components and will also provide a reliability and maintainability data base for the remote maintenance equipment itself. Accurate assessments and design trade-offs of DEMO availability will not be possible without this information from ITER.

Physics Phase Operation Schedule

The operating schedule for the physics phase of ITER seems unrealistically short in several respects. The reliable delivery into high-quality plasmas of 100 MW of auxiliary power, consisting of three distinct technologies, will likely take longer than the one year now envisioned. The reliable operation of highly complex control and safety systems, which will require input from many "real-time" diagnostics, will take valuable machine time which has apparently not been allowed for in the plan. Maintenance of both internal and external hardware, which must be done by fully remote operations in the D-T phase, will likely take more than the 1.5 years of downtime allowed in the 6 year physics phase. It is important from the point of view of reducing the physics phase to have every system installed, tested and operational before the tokamak operation begins. Finally, the operating machine time allotted to produce the physics information expected from the physics phase is unrealistically short. For comparison, the physics program planned for BPX is estimated to require ~ 8 years, and the BPX burning-plasma physics issues are only a subset of those which are planned to be investigated in ITER.

In light of the above considerations, a much more realistic estimate of the time required for the physics phase might be closer to 10 years, rather than the 6 years now envisioned. An unfortunate consequence is that the technology phase could only begin at a time when, based on past experience, the ITER machine may be experiencing aging problems requiring more frequent or extended maintenance. If, on the other hand, a burning-plasma experiment and a long-pulse or steady-state high-performance device could operate well in advance of ITER, the information provided by these devices could shorten the physics phase to as little as 5 years. This is highly desirable if ITER is to have a realistic potential for meeting its technology goals and accomplishing its programmatic objectives.

Technology Phase Operation Schedule

The eight years presently envisioned for the technology phase have been extended about 2-4 years. The resulting 10-12 year testing phase will be necessary to achieve the upper fluence objective of 2-3 MW−y/m^2 without requiring availabilities in excess of 20-30%.

Question 5. "Evaluate the adequacy of safety and environmental considerations in the CDR design and assess the plans to address these issues during the EDA."

Finding The status and priority of safety and environmental (S&E) concerns should be upgraded in the EDA phase of ITER. This upgrading should include: (a) appointment of a "Head of ITER Safety" with high-level responsibility; (b) inclusion of specific S&E goals in the "Technical Objectives and Characteristics" section of Annex 2 in the ITER Terms of Reference; and (c) strengthening the emphasis on, and resources for, S&E issues in the ITER R&D plan and in national fusion R&D programs.

The potential for achieving superior S&E characteristics is crucial to the rationale for developing fusion as an energy source. Conversely, if a fusion device of the prominence and cost of ITER were to be constructed without sufficiently demonstrating many of the features for fusion's S&E potential, the timetable for development and commercialization of fusion could be pushed back by decades. This characteristic of S&E issues is insufficiently appreciated in much of the fusion R&D community, and it is insufficiently reflected in the ITER Terms of Reference, in the ITER R&D Plan, in the ITER Management Structure, and in the priorities of national fusion R&D programs.

In the ITER Terms of Reference, for example, S&E issues are mentioned briefly in the Programmatic Objectives ("demonstrate the potential for safe and environmentally acceptable operation of a power producing fusion reactor" [Sec. 1.2]) but are not mentioned at all in the section on Technical Objectives and Characteristics. Nor was there a Safety and Environment Project Group within the ITER CDA Management Structure; S&E appeared in this structure only as one of the six tasks assigned to the Systems Analysis Project Group. Inadequate appreciation of the importance of S&E issues is also all too evident in the insufficiency of the resources being devoted to S&E in the national fusion R&D programs that provide the technical foundation on which the ITER project must build.

The changes we propose here for elevating the status of S&E issues in the ITER project and related national programs are essential to increase the assurance that construction and operation of ITER will advance rather than set back the prospects for early achievement of commercially attractive fusion power.

Finding The S&E efforts in ITER's CDA phase have provided a good beginning on the needed work of defining appropriate S&E criteria, conducting preliminary safety assessments of the ITER conceptual design, and identifying relevant S&E research needs. However, more attention to certain critical areas will be required before this ITER design or one evolved from it will in fact meet the S&E criteria required for making ITER a success from an S&E perspective.

Notwithstanding the inadequacies of status and resources accorded to S&E efforts so far, as mentioned above, the safety specialists who produced the ITER Safety Analyses Report in the ITER CDA achieved commendable progress in formulating an appropriate set of S&E goals for the ITER project, in conducting a preliminary assessment of the Conceptual Design's capacity to meet these goals, in outlining appropriate directions for the continuation of S&E work in the EDA phase, and in enhancing the awareness of S&E issues in the ITER physics and technology communities. For these solid accomplishments the ITER safety team deserves great credit.

What these wide-ranging and competent S&E analyses from the CDA phase reveal, however, is not entirely reassuring. An ITER built to the Conceptual Design would have a reasonable chance of meeting anticipated regulatory requirements relating to radiological accident risks, but rather high inventories of tritium and conceivably mobilizeable activation products (the latter, above all, from the divertor) mean that the margin for meeting these requirements is small and a degree of accident risk exceeding what is desirable cannot be ruled out -- that is, such a degree of risk is within the uncertainty range of the current assessment by the ITER safety team.

In addition, the emphasis on reactor-accident risks in CDA-phase S&E work, while reasonable from the standpoint of priority-setting under resource constraints, meant that some other potentially important S&E issues have so far received too little attention to provide real assurance that ITER will be seen as a success in S&E terms. These issues include the magnitude of radioactive-waste burdens in comparison with those of fission plants, means of complying with tritium antiproliferation safeguards, hazards of transporting tritium to the ITER site, and (related to all of the other issues) licensability of the ITER facility under the requirements prevailing at the specific site that is chosen.

Finding We concur with the recommendations in the CDR concerning needed efforts in the EDA phase to reduce ITER accident risks and with the uncertainties in accident-risk assessment. Further work on passive means of assuring safety is particularly important. Success in these efforts will require close coordination with both the physics and the technology R&D plans for the EDA phase.

The needed EDA-phase efforts on accident-risk issues include: experimentation and analyses to reduce the uncertainties associated with release fractions of tritium and activation products in severe accidents; reduction of tritium inventories by increasing the burn fraction and reducing the use of carbon in plasma-facing components; investigation of lower-activation divertor concepts; development of means to limit the inventory of erosion dust; development of a rapid, effective, and preferably passive means of plasma shutdown; refinement and implementation of passive means for limiting peak temperatures in plasma-facing components under accident conditions; and detailed engineering and analysis to assure that magnet failures cannot damage the vacuum chamber, coolant lines, tritium systems, or confinement barriers.

It is not only the attainment of superior safety performance that is important to the commercial competitiveness and social acceptance of fusion energy, but the *demonstrability* that superior safety has been attained. The requirement of demonstrability puts particular stress on the use of passive means for assuring that the consequences of malfunctions can be kept within tight limits. Passive approaches were emphasized in the CDA safety work and deserve continuing attention in the EDA phase.

Passive approaches to safety are especially demanding of coordination between safety considerations and the other aspects of reactor design. In this connection, we note that the EDA-phase Physics R&D Plan already contains the needed safety-related items (including, especially, increasing the tritium burn fraction, understanding and controlling plasma disruptions, and investigating advanced divertor concepts), but the Technology Plan is missing some needed S&E elements (including, especially, work on activation product volatility and confinement and on magnet failures). Appointment of a Head of ITER Safety, as recommended above, would help assure that the needed S&E elements receive adequate attention in the implementation of both physics and technology R&D.

Finding S&E efforts in the EDA phase need to give more attention to remote maintenance and decommissioning, radioactive waste characterization and minimization, means of compliance with tritium safeguard requirements, minimizing hazards of tritium shipment, and site-specific aspects of S&E.

Remote-maintenance capabilities are an S&E issue as well as a technological and economic one: these capabilities will be crucial to minimizing worker exposures to radiation, may also be important in limiting public exposures in the aftermath of accidents, and certainly will be essential in dealing with the strongly S&E-related issue of reactor decommissioning. We are not convinced that remote-maintenance capabilities are receiving an amount of effort in ITER (or in the context of national programs) commensurate with their importance.

The diversity and confusion in the area of national standards relating to the management of radioactive wastes must not be allowed to inhibit efforts in the fusion community in general, and the ITER project in particular, to develop meaningful criteria for judging waste hazards and to assure that ITER and other fusion devices achieve superior performance in meeting such criteria. Neither volume nor tonnage of radioactive wastes is a meaningful measure of hazard or of the magnitude of the waste-management task; and the use of such figures out of the context of measures of radiotoxicity and longevity runs the risk of obscuring -- or not obtaining -- the potential advantages of fusion in relation to wastes.

Management of tritium is an issue not only in relation to accident risks and routine radiation exposures of workers and members of the public, but also in relation to providing assurance that tritium is not being diverted from fusion facilities for weapons purposes. It is quite possible that some existing safeguards guidelines for assuring the whereabouts of tritium within a given facility would be very difficult for ITER (and future fusion facilities) to meet. More attention is needed to the means by which fusion facilities could meet stringent tritium safeguards requirements, as well as to the question of how stringent such requirements need to be in light of a realistic assessment of tritium's contribution to proliferation hazards.

It is possible that shipment of tritium from external sources, needed to supplement the tritium produced in the ITER blanket, will pose safety and/or safeguards issues at least as difficult as those posed by tritium within the facility. This is a strongly site-specific issue. It and other site-specific S&E issues will need much more systematic and detailed attention in the EDA than was possible under the constraints of the CDA; for this purpose, it will be necessary to obtain from each ITER Party detailed information on the characteristics of candidate sites and all of the relevant approval processes and standards.

Finding Assuring satisfactory progress toward demonstrating in sufficient degree the S&E potential of fusion will require more emphasis, in both the ITER project and in the national fusion R&D programs, on development and application of advanced reactor materials.

Adequate progress toward realization of the S&E potential of fusion energy -- in ITER's EDA phase and beyond -- is very likely to require a level of effort on development and testing of advanced reactor materials that goes far beyond the extremely modest materials R&D efforts now embedded in the ITER project and in national fusion R&D programs. While it is unlikely that advanced materials can be developed quickly enough to be used in a major way in ITER, it is important that development of such materials be sufficiently advanced by the time ITER is operated so that they can be tested in the fusion environment that ITER provides.

The development of improved materials in parallel with the ITER project is also important in order that solutions be "in sight" for S&E problems that ITER operation is likely to underscore (such as high tritium inventories in plasma-facing components and high mobilizeable activation in the divertor). The ITER device will not, and need not, display all of the attractive S&E characteristics that one expects from the more advanced reactor designs to follow; but the ITER project and fusion developments proceeding in parallel with it do need to show progress toward solutions of any S&E problems that seem likely to be troublesome. If ITER demonstrates S&E problems whose resolution clearly will require new materials, and if coincident with this demonstration there is no progress on development of such materials to which one can point, it will be a serious setback to fusion's prospects for commercialization.

To continue to fail to take seriously the need to develop better fusion-reactor materials -- or to establish convincingly that existing candidate materials will in fact be adequate -- is to place at risk not only the success of the ITER project but also the longer-term prospects of fusion as an attractive energy source.

Question 6 "Assess the adequacy of cost and schedule estimates in the CDA for the design, construction, and assembly of the ITER facility and or the technology R&D program during the EDA."

Finding The CDA design construction cost estimates are likely to be low by at least $1B, even using the ITER costing assumptions. In addition, the ITER assumptions may well underestimate the level of QA activities, component testing, and NASA- or nuclear-grade construction necessary to assure the required level of reliability.

The ITER team examined component costs at the detailed component level, generally using cost experience for the available data base on TFTR, JET, JT-60, and the BPX estimates. Efforts were made to cost some components to nuclear standards (e.g., fuel cycles). Costs associated with the interface between components or systems and the cost of maintenance and guaranteeing the reliability of systems received less attention. The components were apparently costed on present fusion experience, which may well not represent the unit costs associated with comparable reliability programs, such as NASA flights or nuclear reactors.

Several specific areas of concern will add cost (some of which, we realize, were excluded by the ITER costing assumptions):

i) The cost of diagnostics beyond that required for control were not included. This could add $200-300 M.

ii) The average costing of $3/watt for the auxiliary heating systems is low relative to present experience, even allowing for economy of scale and larger unit power sources. When allowance is made for the demands of reliability, remote handling, and the developmental nature of many components, the unit cost may rise significantly.

iii) It may be necessary to include the cost of spares for key components (e.g., a TF coil), and more redundancy (e.g., an outer PF ring coil) to avoid unacceptable downtimes following a system failure.

iv) Greater attention to safety and environmental attractiveness could raise costs of selected components (e.g., isotopic tailoring of tungsten in the divertor to reduce activation.)

v) The overall contingency of 18% would appear low, given that the contingency on components such as the auxiliary heating is taken at 30%.

vi) It is difficult to judge whether sufficient engineering has been included in all phases of construction from the information presented. The ratio of design and title III engineering to investment (17%) is, however, comparable to JET.

Finding The Operations Phase costs appear low in regard to physics staff, spares, and replacement costs.

Based on current experience, we estimate that it will be necessary to add $30-65 M per year to the CDA estimates to adequately staff the physics effort during the operations phase. With regard to spares, JET spent an average of 4.6% of investment between 1984 - 1990 for spares, whereas ITER allows only 2.5%. The replacement costs for the divertor may also be substantially underestimated, depending on survivability. The divertor replacement could easily dominate availability in both the physics and technology phases, with an estimate of 3-6 months for full replacement.

Finding The total construction schedule time of 5 years plus 3 years commissioning time appears reasonable based on experience with JT-60, JET and TFTR. The operations schedule, however, appears overly optimistic.

The ITER project has not devoted resources to producing a detailed schedule, and it is therefore not clear that the EDA will provide timely information in all areas, nor whether sufficient time has been left after the EDA to provide the additional required R&D. Approximately $300 M of R&D has been delayed until after the EDA.

The operations schedule appears optimistic in several regards:

i) Based on present experience (even JT-60) it is optimistic to assume that 100MW of auxiliary power could be delivered to and successfully absorbed in the plasma one year after operations start.

ii) The 3 month breaks between operating periods are unrealistic given the experience on the large "hands-on" tokamaks and given the 3-6 month estimate for divertor replacement.

iii) The lack of a specific plan to maintain the tokamak in the face of failures in the semipermanent structure (e.g., magnets) calls into question the credibility of the D-T schedule.

It would be more realistic to call for more than one year downtime between phases to accommodate slippage and repair or replacement, particularly if a PFC changeout is required.

Finding Technology R&D costs projected for the EDA are success oriented, and they are roughly estimated by the ITER team to depend on $200-400 M of Base Programs which may or may not exist at any level.

The ITER R&D plans are success oriented, and tend to be confirmatory rather than exploratory in their philosophy. It is not clear how advanced concept ideas, (e.g., in the divertor area) are to be funded. It is also not clear how the integration of the technology R&D with the voluntary physics R&D, (e.g., again in the divertor area) will be handled without incurring schedule and cost increments.

The cost philosophy for technology R&D taken by ITER management has been to assume that ITER will pay only for incremental costs associated with ITER-specific R&D. For example, if a particular activity should require only part time from an expert group, or partial use of a measurement facility, only the incremental cost has been included. This clearly requires the existence of Base Programs. The ITER team members were asked to estimate the size of programs that they might assume, and their rough estimates totaled in the range of 200-400 M$. The need for parallel Base Programs will be a particular problem in the U.S., where such programs, if they exist at all, are being re-labelled as ITER.

The cost of the EDA design activity, particularly in the area of the Home teams, is also considered low. This is again a particular U.S. problem, where we do not have a parallel NET-like activity. The U.S. should examine how it might leverage the home team activity by a closer association with the BPX activities.

SEC 3. ADDITIONAL CONSIDERATION

Proposed EDA Management Structures

Although not in response to a question contained in the charge, the Committee examined the draft document "QED Working Party's Consolidated, Common Elements of an ITER EDA for Exploratory Discussion" with the following conclusions:

Finding The QED working party document on a proposed EDA organization is a very good starting point, and should emulate the very successful JET and CERN organizational models.

The QED working party's document indicates that substantial agreement has been reached already between the parties on the organization of the EDA. We raise concerns, however, whether the proposed organization will be as effective as JET and CERN unless extra effort is expended to overcome the complications of the four party structure. The following indicate our specific concerns or have not been sufficiently spelled out in the draft document:

i) The Director and the Central Team should be as autonomous as possible. The relationship of the Director to the Council should be that of a CEO to his Board of Directors. The definition of the "level of business" requiring specific Council approval of Director's decisions should be established.

ii) The make-up and role of the Council is not defined. As the Council is expected to meet only twice per year, we assume that the intent is for involvement at only the highest level. Its areas of attention may be expected to evolve from the initial phase, where concentration will be on promoting international collaboration, to the construction phase, where other priorities will likely dominate. It should not be constituted in a way that invites micro-management. If the Council consists of government officials, separated from the day-to-day operations of the fusion program, it will not be in a position to make key technical decisions. In such cases there is is a tendency to turn to technical committees, an interface that we believe is generally better made at the level of the Director.

iii) The Home Team Leader is specified to be responsible to the Director. How he relates to the Home Team Sponsor (DOE, Euratom, JAERI, etc) is not defined, but should be addressed as a high priority issue by the home countries. The arrangements should optimize the ability of the Home Team Leader to carry out his responsibilities to the ITER Director.

iv) It is not clear to what extent the Director has the discretion to initiate new work (i.e., not in the original R&D lists). It is also not clear how he can assure that particularly high-priority physics work is done. It would be advantageous for the Director to have direct control of some level of funds (or credits) to directly sponsor work in associated laboratories and in industry, in order expeditiously to cover unforeseen problems. The JET arrangements can serve as a good model.

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