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Panel Report To Fusion Energy Sciences Advisory Committee (FESAC)

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"Review of the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report"

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This report was prepared by a Panel established by, and reporting to, the Fusion Energy Science Advisory Committee (FESAC). The report of this Panel has been endorsed by FESAC.

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I. Executive Summary

ITER, the International Thermonuclear Experimental Reactor project, is now in the Engineering Design Phase (EDA) of a worldwide effort to conceive, design and ultimately construct an experimental device to advance the development of fusion power. The major partners in the ITER effort are the European Union, Japan, the Russian Federation and the United States, and the EDA phase of the program is scheduled to be completed in 1998.

The objectives of ITER are "...to demonstrate controlled ignition and extended burn ...," "...to demonstrate steady-state operation..." and "...to demonstrate the technologies essential for a fusion reactor...." ITER brings together three threads important for the advancement of fusion: burning plasma physics, steady-state operation, and the testing of key technologies. It has long been agreed in the US fusion program that the threshold to burning plasma physics occurs at $Q = 5$, where the alpha heating power equals the externally supplied input power. Technology testing of divertor systems and plasma facing components, as well as qualification of nuclear blanket modules, requires at least 1 GW of fusion power in ITER, with a neutron fluence of about 1 MW-yr/m^2 accumulated over a period of about 10 years. Thus if ITER can achieve $Q > 5$ for long pulses at $P_{fus} > 1$ GW, with an availability of 10 - 15%, this will constitute a dramatic step toward demonstrating the scientific and technological feasibility of fusion energy. Together with further improvements in plasma performance and plant availability in the ongoing fusion science and technology programs, results from ITER will provide critical information required for the design of an attractive fusion DEMO power plant.

The general objectives and the plasma performance and engineering performance objectives for ITER are specifically set out in the 1992 report of the Special Working Group-I (SWG-I) as:

General

"The ITER detailed technical objectives and the technical approaches, including appropriate margins, should be compatible with the aim of maintaining the cost of the device within the limits comparable to those indicated in the final report of the ITER CDA as well as keeping its impact in the long-range fusion program. ITER should be designed to operate safely and to demonstrate the safety and environmental potential of fusion power."

Plasma Performance

"ITER should have a confinement capability to reach controlled ignition. The estimates of confinement capability of ITER should be based, as in the CDA procedure, on established favorable modes of operation. ITER should demonstrate controlled ignition and extended burn for a duration sufficient to achieve stationary conditions on all time scales characteristic of plasma processes and plasma wall interactions, and sufficient for achieving stationary conditions for nuclear testing of blanket components. This can be fulfilled by pulses with flat top duration in the range of 1000 s. For testing particular blanket designs, pulses of approximately 2000 s are desirable, with the ultimate aim of demonstrating steady state operation using non-inductive current drive in reactor relevant plasmas."

Engineering Performance and Testing

"ITER should demonstrate the availability of technologies essential for a fusion reactor (such as superconducting magnets and remote maintenance); test components for a reactor (such as exhaust power and particles from the plasma); test design concepts of tritium breeding blankets relevant to a reactor. The tests foreseen on modules include the demonstration of a breeding capability that would lead to tritium self-sufficiency in a reactor, the extraction of high-grade heat, and electricity generation."

The remainder of the SWG-1 report outlining the design and operation requirements is given in Appendix B. Commitments by the parties to proceed to construction and a decision on selection of the construction site are scheduled for the 1998 time frame. All parties recognize the importance of ITER, both to their national fusion efforts and as an opportunity to do cooperative international science on an unprecedented scale. As recently as Fall 1996, a meeting of some sixty U.S. fusion program leaders reaffirmed support for U.S. participation in ITER and ITER's importance as an investment in fusion research, even if the U.S. participation were on the basis of a less-than-full member. There was a strong consensus that, at present U.S. fusion funding levels, continuation of the present funding level into the ITER construction phase is very well justified.

Dr. Martha Krebs, Director, Office of Energy Research at the U.S. Department of Energy (DOE), wrote to the Fusion Energy Sciences Advisory Committee (FESAC), in letters dated September 23 and November 6, 1996, requesting that FESAC review the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report (DDR) and "provide its view of the adequacy of the DDR as part of the basis for the United States decision to enter negotiations" with the other interested Parties regarding "the terms and conditions for an agreement for the construction, operations, exploitation and decommissioning of ITER." The letter from Dr. Krebs provided context for the review and specifically asked that the following five questions be addressed:

1. Are the ITER physics basis, technology base, and engineering design sound? Focus on the critical physics, technology, and engineering issues that affect the design while allowing for the R&D planned in each of the areas through the end of the EDA.

2. Is ITER likely to meet its performance objectives as agreed upon by the four Parties and documented in the 1992 SWG-1 report? Evaluate predicted performance margins, comment on the range of operating scenarios, and identify opportunities to improve the performance.

3. Do the design and operating plans adequately address environment, safety, and health concerns? Focus on the methodology used by the Joint Central Team to address these concerns.

4. Are the proposed cost estimates and schedules for the construction project and subsequent operations, exploitation and decommissioning credible, and are they consistent with the procurement methods and staffing arrangements recommended by the ITER Director? Focus on the methodology used to prepare the estimates.

5. Are there any cost effective opportunities for pursuing modest extensions of the current design features in order to enhance operational flexibility and increase scientific and technological productivity of ITER? Focus on areas where cost effectiveness of any design extensions would be high.

In this Executive Summary, the Panel provides our primary findings, conclusions and recommendations. These will be given in the form of direct responses to the specific questions asked of FESAC by Dr. Krebs. We will also provide specific references to the chapters in the body of the report where a much expanded discussion is given relating both to these questions and other issues important to the ultimate success of the ITER project. The Panel did develop a significant number of other findings and recommendations relating to more specific issues, often about particular ITER subsystems. These are included in the body of the report, and often in the subpanel reports as well. The Panel and its subpanels offer these findings and recommendations to the ITER Joint Central Team (JCT) as it begins preparation of the ITER Final Design Report. For ease of reference, we repeat each question and then provide our response.

Question 1. Are the ITER physics basis, technology base, and engineering design sound? Focus on the critical physics, technology, and engineering issues that affect the design while allowing for the R&D planned in each of the areas through the end of the EDA.

Important issues in evaluating the design basis deal with the physics operation, with the new elements of the operation (burning-plasma and steady-state physics), with the technologies necessary to address these physics issues, and with the engineering design itself. Key issues include the readiness of fusion to embark on a program step having ITER's goals and the basis of confidence that ITER can reach the conditions necessary for achieving its objectives. The Panel's assessment of the physics basis for the design, and of the basis for physics-related subsystems is discussed in Chapter IV. The Panel's assessment of the engineering features of the design, specifically the likelihood that the experimental apparatus will meet its design specifications, and that it can be operated and maintained in a fashion that will meet the overall ITER program objectives, is given in Chapter V. The response we give here is repeated and expanded upon in these two Chapters.

Findings and Conclusions Regarding Question 1: The ITER Design Team has drawn widely from the world tokamak experience-base and has involved experts worldwide to produce a credible machine design. The Panel has not identified from this experience-base any insurmountable obstacles in its plasma engineering and electro-mechanical engineering that would prevent ITER from achieving its objectives. However, there are specific areas that require further attention, priority R&D, and resolution. Our overall assessment is that the ITER engineering design represented in the DDR is a sound basis for the project and for the DOE to enter negotiations with the Parties regarding construction. The subpanels noted that some aspects, such as the design of the magnet systems, are more fully developed and more mature than would normally be the case at this stage of a project. In certain other areas, such as the first wall and the bolted blanket/shield approach, it is not yet clear whether the present design can meet its performance requirements, and focused efforts are underway to develop final designs. A theme throughout the subpanel recommendations is a need for formal, quantified reliability, availability, and maintainability (RAM) requirements and analyses. The subpanels noted a number of other areas that will need focused R&D and detailed design efforts in the post-EDA period.

Question 2. Is ITER likely to meet its performance objectives as agreed upon by the four Parties and documented in the 1992 SWG-1 report? Evaluate predicted performance margins, comment on the range of operating scenarios, and identify opportunities to improve the performance.

ITER is clearly of the scope and scale required to explore extended-pulse, self-heated fusion plasma physics. However, in assessing ITER's anticipated performance, it is important to do so in the context of ITER as a scientific experiment — the first attempt at magnetic fusion ignition and controlled burn. In particular, to reach its peak performance, ITER will extend issues such as confinement, pulse-length and alpha-heating effects far beyond those attained in present-day tokamaks. As such, predictions for its performance cannot be made precise, given the experimental nature and goals of the ITER program. The best that can be given are predictions of most probable performance, together with the associated uncertainty, for each of the individual aspects and hence for ITER as a whole. In the end, the judgment that must be made, as with any scientific experiment, relates to the balance between design risk and design conservatism, given the present state of knowledge and the objectives and goals of the experiment. The findings and conclusions presented next are expanded upon in Chapter VI.

Findings and Conclusions Regarding Question 2. In the Panel's estimation, based on extrapolated tokamak confinement data, the expected performance of ITER's base operating mode (ELMy H-mode confinement) ranges from that of fusion ignition ($Q \rightarrow \infty$) to a moderately self-heating burning plasma ($Q \sim 4$). (Here Q is the ratio of fusion power produced to energy input to sustain the plasma.) There is high confidence that ITER will be able to study long pulse burning plasma physics under reduced conditions ($Q \gtrsim 4$), as well as provide fundamental new knowledge on plasma confinement at near-fusion-reactor plasma conditions. Achieving long pulse ignition cannot be assured, but remains a reasonable possibility. The Panel concludes that the DDR incorporates significant flexibility within the design and costs constraints, through multiple options to explore combinations of heating, fueling, shaping, and current drive control. Additional analysis is called for to insure adequate flexibility to access advanced confinement regimes. The Panel also recommends that flexibility for additional heating power be made available in case it is needed to provide adequate neutron wall loading, as well as adequate plasma stored energy (beta) and power flow across the separatrix. This will give confidence of access to the H-mode, as well as permit ITER to achieve the necessary physics and technology tests, even if the plasma performs near the low end of its predicted confinement range. To assure the upgradability of the heating and current drive systems to approximately 200 MW (if needed), the design team should carefully assess the implications for port space, auxiliary areas, and site power.

The Design Team has focused its attention and resources so far primarily on successful operation in the Basic Performance Phase, with the view that the knowledge and experience gained in this phase will guide the Enhanced Performance Phase. Consequently, achieving the Basic Performance Phase objectives looms large in the DDR design, and the Enhanced Performance Phase objectives have not been addressed beyond assuring capability of the facility to address those objectives.. The Panel concurs with this approach.

Question 3. Do the design and operating plans adequately address environment, safety, and health concerns? Focus on the methodology used by the Joint Central Team to address these concerns.

ITER is a large and complex device which will use tritium as a fuel and produce energetic neutrons as an output. Careful tracking and control of the tritium inventory will be required and in this connection, removal of tritium from the first wall of the vessel remains an outstanding issue. As a result of neutron bombardment, the machine structure and surrounding materials will become activated. The ITER device will require a nuclear license to operate wherever it is sited, yet is unlike any other device that has been licensed previously. Detailed safety requirements have been established based on recognized international safety criteria. These limits are not always as restrictive as U.S. limits, but upgrading the design to meet U.S. regulations is not a fundamental concern. Safety requirements have been an integral part of the overall design requirements. Careful analysis has been done to show that the facility will operate within these requirements in both normal and accident scenarios. These analyses have been carried out using the best available understanding and computer codes. The project has, as a design requirement, the avoidance of the need to evacuate the general public following the most serious accident. A general project objective is that the dose to workers and the public be maintained as low as reasonably achievable (ALARA). The findings and conclusions presented next are expanded upon in Chapter VII.

Findings and Conclusions Regarding Question 3. The ITER team has an appropriate organization in place to address nuclear issues and has, in general, addressed these issues in an appropriate manner. The nuclear design effort has been the subject of a recent review by the four parties within the ITER framework and the work done has been documented in the Non-site Specific Safety Report (NSSR-1). The safety aspects of the design and analysis are adequate for this stage of the project.

Question 4. Are the proposed cost estimates and schedules for the construction project and subsequent operations, exploitation and decommissioning credible, and are they consistent with the procurement methods and staffing arrangements recommended by the ITER Director? Focus on the methodology used to prepare the estimates.

The cost and schedule development process used by the JCT is based on a detailed set of procedures and formats that facilitated a standardized and consistent cost and schedule estimate. For many components, and for virtually all of the tokamak components, industrial estimates have been obtained from multiple Parties (herein to be understood as industries of those Parties) in preparation for the Interim Design Report (IDR). For some components, estimates were obtained from a single Party, and for buildings, diagnostics, and machine tooling they were internally generated by the JCT. The IDR Cost Estimate represented a bottoms-up estimate of almost every element of ITER. The cost and schedule issues are discussed in greater detail in Chapter VIII.

Findings and Conclusions Regarding Question 4. In the Panel's judgment, the JCT has done a disciplined and thorough job in gathering the complex data from diverse parties and developing a self-consistent cost and schedule data-base predicated on sound cost and schedule estimating methodologies. Estimates for components and systems are primarily based on industrial estimates from multiple parties, and have been extensively analyzed and processed to insure credibility, completeness and accuracy. Overall, the Panel judges the cost estimate to be reasonable and sound for this stage of the project. The Panel does note that the plan is a success-oriented one, in that there is little or no budget or time allotted to accommodate unforeseen problems that may arise. An efficient management structure and procurement system, taking maximum advantage of industrial competition in bidding, is required during construction to meet the aggressive cost and schedule goals of the project.

Question 5. Are there any cost effective opportunities for pursuing modest extensions of the current design features in order to enhance operational flexibility and increase scientific and technological productivity of ITER? Focus on areas where cost effectiveness of any design extensions would be high.

The ITER design is a complex one and the Panel is well aware of the time and effort needed to determine if any design suggestion, either for modification or extension, is one that can meet the design requirements and system specifications established to ensure the credibility of the engineering design itself. Given this, and given the short time available to the Panel to conduct this review, the Panel has chosen not to focus on this question. However specific suggestions are included in the bulk of the panel report, and in the appendices - especially in the area of flexibility - which we think are worthy of careful review by the ITER team. Indeed many of these are already under study by the ITER Joint Central Team and the various Home Teams.

In closing, the Panel would like to re-affirm the importance of the key elements of ITER's mission - burning plasma physics, steady-state operation, and technology testing. The Panel has great confidence that ITER will be able to make crucial contributions in each of these areas. While we have identified some important technical issues, we have confidence that the ITER team will be able to resolve these issues before the Final Design Report (FDR). Furthermore, even in the unlikely circumstance that the ITER plasma performs at the lower end of its predicted range, heating and current drive upgradability to ~200 MW would provide greater confidence that ITER will be able to fulfill its programmatic role. The achievement of ITER's mission will be a major milestone in the development of a safe, economic, and sustainable energy source for the future.