ITER-FEAT - The Future International Burning Plasma Experiment Overview

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Abstract: The focus of effort in the ITER Engineering Design Activities (EDA) since 1998 has been the development of a new design to meet revised technical objectives and a cost reduction target of about 50% of the previously accepted cost estimate.
Drawing on the design solutions already developed and using the latest physics results and outputs from technology R&D projects, the Joint Central Team and Home Teams, working jointly, have been able to converge towards a new design which will allow the exploration of a range of burning plasma conditions, with a capacity to progress towards possible modes of steady state operation.
As such the new ITER design, whilst having reduced technical objectives from its predecessor, will nonetheless meet the programmatic objective of providing an integrated demonstration of the scientific and technological feasibility of fusion energy.
The main features of the current design and of its projected performance are introduced and the outlook for construction and operation is summarised.

1. Introduction

The motives for developing fusion as an energy source lie in its attractions as a possible large scale contributor to the energy mix in the second half of this century, with virtually inexhaustible fuel supply, good safety characteristics and an acceptable environmental impact. These incentives have been driving the world fusion research programme since its inception. Continuing population growth and the growing economic aspirations of all mankind, combined with the increasing international concern over the potential climatic threat from dependence on fossil fuels, reinforce the case for providing a range of practical energy options for sustainable energy supply. Establishing the fusion energy option can make a critical contribution to the welfare of future society.

After the impressive progress in recent years to bring the fusion research programmes to the threshold of reactor conditions in both physics and technology, the imperatives for future progress in fusion are now:

- in physics, to move across the threshold into fusion conditions that current machines cannot access, in particular to reach the point at which energetic α-particles become the main source of plasma heating and the principal determinant of plasma behaviour.
- in technology, to combine and test key features of fusion reactor technology in reactor-relevant conditions;
- in terms of public acceptance, to demonstrate in reality the favourable safety and environmental characteristics of fusion.

2. Summary of Progress of ITER to 1998

The ITER project has its origins in a common recognition among the leading fusion programmes world-wide of the need for a next step experiment with the programmatic objective of demonstrating the scientific and technological feasibility of fusion energy for peaceful purposes [1]. Building on the performance advances of leading machines and the wider database from both small and large machines, ITER has the core of a working fusion reactor and is thus designed to embody the next step machine that serves the imperatives above.

The technical conditions of a burning plasma experiment themselves demand the use of advanced fusion technologies. In addition, the integration of burning plasma physics with fusion technologies is an essential step on the strategic path towards establishing the fusion energy option. In enabling, in one device, full exploration of the physics issues, as well as proof of principle and testing of some key technological features of possible fusion power stations, ITER would provide the basis for design of a first demonstration fusion power station that would demonstrate the reliable generation of electricity, before a prototype power plant could be envisaged for commercial use on competitive grounds.

The ITER collaboration was set up to provide its Parties the option to make the next step within a frame of global collaboration in which participants could pool their accumulated scientific and technological expertise, share the burden of costs, and secure a degree of political commitment consistent with the scope and time-scale of the task.

Six years of joint work under the EDA Agreement [1] yielded a mature design, cost estimate and safety analysis - the ITER 1998 design [2] - that was supported by a body of validating physics and technology R&D. The 1998 design met the detailed objectives that had been set for it in 1992, focussing on plasma ignition ($Q = \infty$) in reference inductive operation, with margins in physics and technology to allow for unqualified design concepts, whilst satisfying the cost target originally set for it.

At that point, the Parties negotiated a three year extension to the original EDA in order to prepare for a decision to build. At the same time, in view of financial pressures, the Parties undertook a review of the detailed technical objectives to explore the scope for cost savings that might be possible whilst still serving ITER's overall programmatic objective.

3. Revised Guidelines for ITER Design

The revised guidelines for ITER [3] require in terms of plasma performance

- to achieve extended burn in inductively-driven plasmas at $Q > 10$ for a range of scenarios, whilst not precluding the possibility of controlled ignition.
- to aim at demonstrating steady-state operation through current drive at $Q > 5$.

In terms of engineering performance and testing, the new design should

- demonstrate availability and integration of essential fusion technologies,
- tests components for a future reactor, and
- test tritium breeding module concepts, with the 14 MeV-neutron power load on the first wall ≥ 0.5 MW/m^2 and fluence ≥ 0.3 MW.a/m^2.

The new design should aim for a cost target of about 50% of the costs of the 1998 ITER design.

4. Convergence to the New Design Point

As a first approach to identifying designs that might meet the revised objectives, system codes were used in combination with costing algorithms to establish possible feasible design points for further analysis. The systems approach combined a detailed plasma power balance and boundaries for the window of plasma operating parameters, providing the required range of Q for the D-T burn, with engineering concepts and allowable limits. Four key parameters — aspect ratio, peak toroidal field, plasma elongation, and burn flux — are intimately linked, allowing options in the systems analysis to be characterised principally by the aspect ratio, in addition to the device size. Access to the plasma (e.g. for heating systems) and allowable elongation (simultaneously constrained by plasma vertical position and shape control, and by the necessary neutron shield thickness) are functions of aspect ratio.

On this basis, the system studies indicated a domain of feasible design space, with aspect ratios in the range 2.5 to 3.5 and a major radius around 6 m, able to meet the modified requirements, with a shallow cost minimum across the range.

In order to provide a basis for rigorous exploration and quantification of the issues and costings, representative options that span an appropriate range of aspect ratio and magnetic field were selected for further elaboration and more comprehensive consideration. With this more tangible appreciation of the key issues, joint JCT/Home Team Task Forces were able to converge progressively towards a preferred outline design point taking the following as guiding principles:

- to preserve as far as possible physics performance and margins against the revised targets, and the scope for experimental flexibility, within the cost target and relevant engineering constraints;
- to exploit the recent advances in the understanding of key physics and engineering issues drawn from the results of the ITER voluntary physics programme and the large technology R&D projects;
- to maintain the priority given to safety and environmental characteristics, using the principles, analyses and tools developed through the ITER collaboration to date.

The resulting configuration for the new design of ITER (referred to as ITER-FEAT) [4] represents an appropriate balance of the key technical factors and the cost target and the use of conservatism for energy confinement scaling.

5. Parameters and Plasma Performance of the New ITER Design

The main parameters and overall dimensions of the ITER-FEAT plasma are summarised in Table 1 below. The figures show parameters and dimensions for nominal operation. Figures in brackets represent maximum values under specific limiting conditions, including, in some cases, additional capital expenditures. A cross-section of the tokamak is shown in Figure 1 and a cutaway view of the tokamak and sub-sytems in the cryostat are shown in Figure 2. The performance is discussed in more detail elsewhere [5-7].

TAB. 1: MAIN PARAMETERS AND DIMENSIONS OF THE ITER-FEAT PLASMA

Total fusion power	500MW *(700 MW)*
Q — Fusion power/auxiliary heating power	≥ 10
Average neutron wall loading	0.57 MW/m^2 *(0.8 MW/m^2)*
Plasma inductive burn time	≥ 300 s.
Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Plasma current (I_p)	15 MA *(17.4 MA)*
Vertical elongation @95% flux surface/separatrix	1.70/1.85
Triangularity @95% flux surface/separatrix	0.33/0.49
Safety factor @95% flux surface	3.0
Toroidal field @ 6.2 m radius	5.3 T
Plasma volume	837 m^3
Plasma surface	678 m^2
Installed auxiliary heating/current drive power	73 MW *(100 MW)*

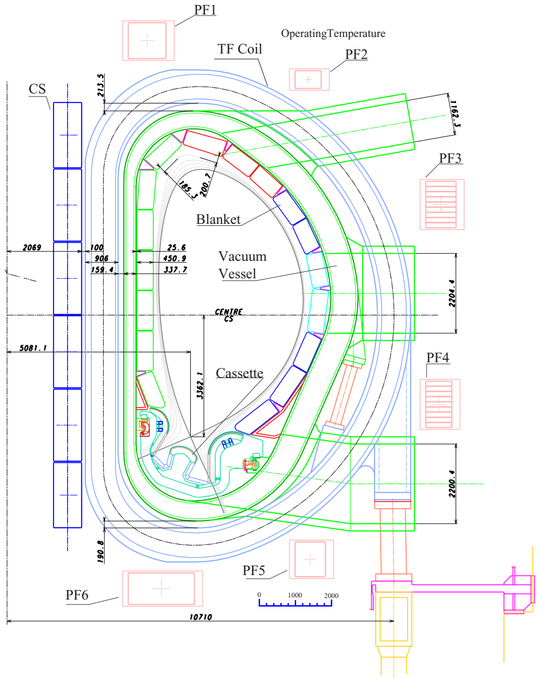

FIG. 1. Cross-section of the ITER tokamak

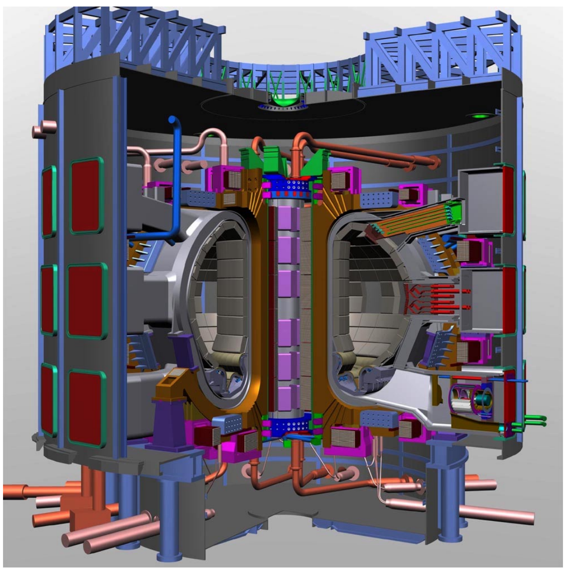

FIG. 2 Cutaway view of ITER

5.1 Inductive Operation

The reference operating scenario for inductive operation is the ELMy H-mode, and the rules and methodologies for projection of plasma performance to the ITER scale are those established in the ITER Physics Basis (IPB) [8], which has been developed from broadly-based experimental and modelling activities within the magnetic fusion programmes of the ITER Parties.

Key limiting factors for inductive operation are normalised β (β_N), density in relation to the Greenwald limit (n/n_{GW}), and the L-H mode power threshold. A view can be formed of the range of possible plasma parameters at which Q = 10 by analysing, with flat density profile, possible operational domains in relation to the above limiting factors, for given values of Q, plasma current and confinement enhancement factor, H_H, as illustrated in Figures 3a and b.

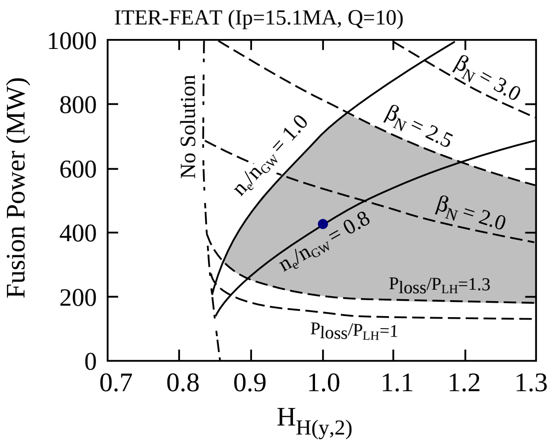

FIG. 3a. Q = 10 domain (shaded) for I_p = 15.1 MA (q_{95} = 3.0).

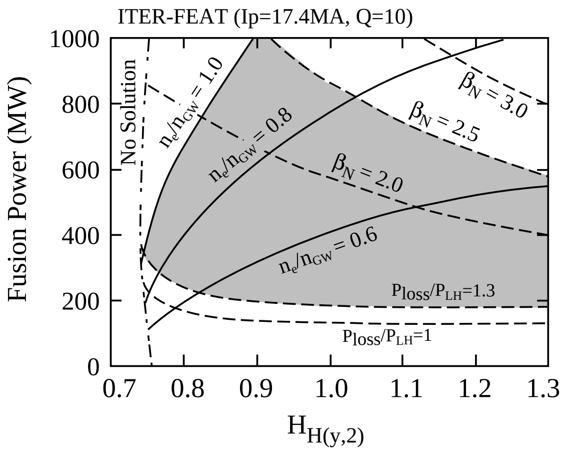

FIG. 3 b. Q = 10 domain (shaded) for I_p = 17.4 MA (q_{95} = 2.6).

It is evident from the figures, that:

- for operation at q_{95} = 3 the fusion output power from the new ITER design is in the region of 200-700 MW (at $H_{H(y,2)}$ = 1), corresponding to a mean separatrix neutron flux ('mean neutron wall loading') of 0.23-0.80 MWm^{-2}, so that the device retains a significant capability for technology studies, such as tests of tritium breeding blanket modules;
- the margin in H-mode threshold power (at $H_{H(y,2)}$ = 1) is significantly greater than the predicted uncertainty derived from the scaling;
- the device has a capability for Q = 10 operation at n/n_{GW} ~ 0.7 and β_N ~ 1.5 (when $H_{H(y,2)}$ = 1).

The results also illustrate the flexibility of the design, its capacity for responding to factors which may degrade confinement while maintaining the goal of extended burn Q > 10 operation, and, by the same token, its ability to explore higher Q operation as long as energy confinement times consistent with the confinement scaling are maintained. For instance, operation at a range of Q values is possible and values as high as 50 can be attained for nominal parameters if $H_{H(y,2)}$ ~ 1.2 in an improved confinement mode, e.g. reversed shear or shallow shear mode with internal transport barrier or, as presently observed, if operation at lower q_{95} (~ 2.6) can be sustained without confinement degradation.

Ignition can be achieved, after a few seconds pulse of 73 MW of auxiliary power, with Ip=17 MA, n/nGN=0.8, either limited to about 40 s during the build-up of Helium impirity in the plasma with τ_{He}/τ_E = 5 and HH(y,2) = 1, or as long as the burn flux allows, if the HH factor were improved by 10%.

5.2 Steady-state Operation

Steady-state operation can be regarded as an ultimate goal of the tokamak development programme. Coherent and complete scenarios with supporting databases for possible modes of steady-state operation do not yet exist. The next step experiment should thus be capable of exploring the requirements for steady-state operation. It must also have the built-in flexibility to exploit new developments in the fusion programme as they arise. In ITER it is likely that a variety of candidate steady-state modes of operation will be investigated and it is therefore essential that the requisite tools for the control of plasma geometry and profiles are available.

On-axis and off-axis current drive capabilities will enable plasmas with shallow or negative shear configurations to be sustained, in the latter regime simultaneously maintaining the central safety factor well above unity, while the minimum safety factor is held above two. Other necessary tools include a poloidal field system capable of controlling the more highly shaped plasmas characteristic of high-β_p operation, and methods to allow reliable long pulse operation at high β, including techniques for the stabilization of neoclassical tearing modes and resistive wall modes.

For the new ITER design, possible operational scenarios are being considered for steady-state operation in line with some present experiments and able to provide Q = 5, for example: high current (12 MA) with monotonic q and shallow shear, and modest current (9 MA) with negative shear. The high current steady-state operation requires all the current drive power (100 MW) available for ITER, but the requirements on confinement ($H_H \sim 1.2$) and beta ($\beta_N \sim 3$) are modest. The low current, steady-state operation requires more challenging values of confinement improvement $H_H \sim 1.5$ and beta ($\beta_N \sim 3.2$-3.5). Performance predictions for these modes of operation are much less certain than for inductive operation with a larger power to the divertor. In particular, the operating space is sensitive to assumptions about current drive efficiency and plasma profiles.

5.3 Hybrid Operation Modes

Hybrid modes of operation, in which a substantial fraction of the plasma current is driven, in addition to the inductive part, by external heating and the bootstrap effect, leading to extension of the burn duration, appear to be a promising route towards establishing true steady-state modes of operation. This form of operation would be well suited to systems engineering tests.

Analysis of the operation space, in terms of fusion power versus confinement enhancement factor indicates that, for a given value of fusion power (and hence Q), as the confinement enhancement factor, $H_{H(y,2)}$, increases (simultaneously decreasing plasma density and increasing β_N), the plasma loop voltage falls towards zero. For example (Figure 4), operation with $V_{loop} = 0.02$ V and $I_p = 12$ MA, which corresponds to a flat-top length of 2,500 s, is expected at $H_{H(y,2)} = 1$, Q = 5, $n_e/n_{GW} = 0.7$, and $\beta_N = 2.5$. True steady-state operation at Q = 5 can be achieved with $H_{H(y,2)} = 1.2$ and $\beta_N = 2.8$. This suggests that the ITER design permits a long pulse mode of operation at Q = 5 as an approach to steady-state operation.

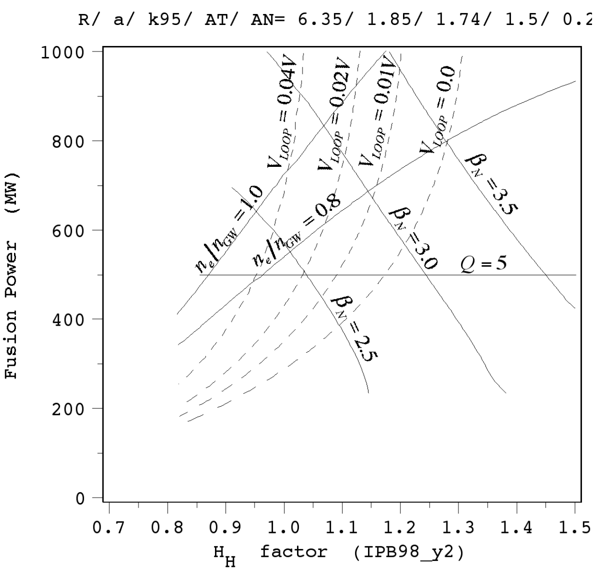

FIG. 4 Operation space for hybrid (long pulse) and steady-state operation. Here, I_p = 12 MA and P_{CD} = 100 MW.

6. ITER Technology and Engineering

6.1 R&D Basis

The overall philosophy for ITER design has been to use established approaches through detailed analysis and to validate their application to ITER through technology R&D, including fabrication of full scale or scalable models of key components.

Significant efforts and resources have been devoted to the seven large R&D projects [9-16], which cover all the major key components of the basic machine of ITER and their maintenance tools. Technology R&D issues for the new design of ITER are largely the same as for the 1998 ITER design. These major projects are all expected to meet their objectives for the EDA: major developments and fabrication have been completed and tests are continuing to demonstrate their performance margin and/or to optimize their operational use.

The technical output from the R&D validates the technologies and confirms the manufacturing techniques and quality assurance incorporated in the ITER design, and supports the manufacturing cost estimates for important key cost drivers. For example, two of these R&D projects, which have already achieved their expected results, are shown in Figures 5 and 6. The former shows the central solenoid outer module being placed outside the inner module, already installed in the vacuum chamber at the test facility in JAERI, Naka where the complete coil has undergone a comprehensive test programme. The latter shows a top view of the divertor remote handling test platform at ENEA, Brasimone.

FIG. 5: Central Solenoid Model Coil Facility

FIG. 6: Divertor Remote Handling Test Platform

The execution of major joint technology projects offers insights for a possible future collaborative construction activity. Valuable and relevant experience has already been gained in the management of industrial scale, cross-Party ventures. The successful progress of these projects increases confidence in the possibility of jointly constructing ITER in an international project framework.

6.2 Design Modifications

Whilst the new design of ITER [17-22] uses, as far as possible, technical solutions and concepts previously developed and qualified during the EDA, the changes in overall scale and in some physics requirements (e.g. more plasma shaping) and the pressure to preserve the plasma performance capacity and flexibility, whilst approaching the 50% cost savings target, have induced some significant changes in the design features from the 1998 ITER design.

In addition, data flowing from the technology R&D projects, in particular the seven large projects, have enabled changes in design criteria associated with a better knowledge of the available margins.

Changes to the engineering features of the design have been influenced by the unwillingness to compromise with physics extrapolation so as to provide enough margins in the physical parameters and physics-related systems e.g., plasma size, fuelling, and heating and current drive, for instance:

- the in-vessel backplate has been eliminated thus allowing the largest possible plasma volume within the reduced overall size of the tokamak;
- the higher plasma shaping introduced to assure the plasma performance targets has necessitated the use of a segmented contral solenoid and enhancements in the stability control system;
- maintaining the size of port access requires some reduction in the inter-coil mechanical structure.

Design changes outside the vessel also balance the general pressure to reduce the dimensions of and simplify ITER systems on cost grounds against the need to maintain the projected level of performance. In the magnet system, the central solenoid being segmented leads to the adoption of a wedged support of the toroidal field (TF) coils (their number is reduced to 18) and to modification in the global mechanical structure; other changes include a quasi-symmetrical poloidal field coil configuration about the equatorial plane.

In the divertor system, a V-shaped configuration of the target and divertor floor was adopted as well as a large opening between the inner and outer divertor legs to allow an efficient exchange of neutral particles; these choices provide a large reduction in the target peak load, without adversely affecting the helium removal.

The reduction in the size and cost of ITER has led to a simplified building and plant layout and the main remote handling systems also have had to adapt to the general reduction of scale.

A major focus of continued design effort is to continue to look for improvement in the manufacturing processes (with their feedback on design) to approach as closely as possible the target of 50% saving in direct capital cost from the 1998 ITER design.

7. Safety Considerations

Safety considerations of the new ITER design [23] remain largely unchanged from the 1998 design. Thus, the favourable evaluation of ITER's safety and environmental characteristics remain valid. Indeed, with a longer initial non-nuclear phase of operations now foreseen for the new design, it will be possible to have a more precise evaluation of the plant characteristics for nuclear operation.

Informal contact has been made with regulatory authorities of the ITER Parties, to prepare for possible licensing actions and with an aim also to develop an international consensus on the safety principles for fusion, so that the experience with ITER can be generalised for application beyond the host country.

The target for the current phase of ITER is to provide a Generic Site Safety Report (GSSR), which will document the safety assessment of the new design, as part of the final output of the ITER EDA. The GSSR is also intended to provide a basis from which to start preparing regulatory submissions for siting, subject to the further site-specific design adaptations and host-country-specific safety assessments that will be needed to obtain regulatory approval for construction.

8. Planned Construction and Operation Costs

The project cost estimate for the 8-year construction of the new design is to be based on an industrial cost analysis undertaken by firms of the Parties in the second half of 2000. Pending such analysis, a simple re-scaling exercise, based on the cost analysis of the 1998 ITER design, indicates an overall reduction to about 56% of the estimated direct capital costs of the 1998 design. The scope to approach closer to 50% will be better understood only after the Parties' industries have had the opportunity to study and estimate procurement packages which incorporate expected improvements in the design and fabrication process. These are now the most important areas of activity for aligning capital costs more closely to the 50% target — US$ 2.9 B (January 1989 value) a figure roughly equivalent to 3.5 BioEuro (January 2000 values), 420 B Yen, 3.9 B US$ when escalated in each Party.

Operating costs for the 20-year operating life of ITER depend highly on the cost of electricity, the salaries of the estimated 200 professionals and 400 support personnel, and the cost of the divertor high heat flux component replacements and general maintenance expenses, most of which may vary quite substantially amongst the potential host sites for ITER. Simple scalings from the operating cost estimates for the 1998 ITER design suggest an indicative annual figure of about 5% of the capital cost over the first ten years of ITER operation, which represents a saving of almost 50% compared to the 1998 ITER design.

9. The Impact of ITER and Future Outlook

9.1 The Benefits of ITER Collaboration

The ITER co-operation to date, in combination with the continuing general progress in fusion research, has brought its Parties and the world fusion development programme to the point at which they are technically ready and able to proceed to construction of a next step tokamak device that bridges the strategic gap between the present generation of large tokamak experiments and a first demonstration fusion power reactor.

Sharing the costs and pooling expertise have allowed the Parties jointly to undertake tasks that would be beyond the financial and/or technical capacity of each individually - as witnessed in the seven large R&D projects. In the process, the Parties have together developed a mature and wide-ranging capacity for successful focussed international joint work, including cooperative problem-solving, as in the efficient co-ordination of the fusion physics programme to establish and extend the physics basis of ITER.

The success of the ITER EDA collaboration demonstrates the feasibility and underlines the desirability of aiming for a joint implementation of ITER in a broad-based international collaborative frame: it supports the Parties' declared policy interests to pursue the development of fusion through international collaboration.

9.2 Need for New Organisation

The ITER EDA Agreement does not commit the Parties to joint construction. Such a move requires new decisions at the highest government levels following negotiations among those interested to participate in the full realisation of ITER.

The current ITER Parties started, in spring 2000, non-committal exploratory discussions as precursors to formal negotiations on a joint implementation of ITER. Critical issues to be settled between the Parties include:

- the establishment of a legal framework for joint implementation that properly reflects various necessary considerations, for instance to provide the focus needed for effective and accountable project management, while ensuring the inclusiveness needed to sustain necessary levels of support and commitment from the wide range of disparate interests throughout the participating countries;
- the settlement of the linked issues of siting, cost sharing and task allocation in equitable ways - with regard to siting, site offers should be presented around Spring 2001, and there are presently efforts to promote interest in potential sites in Europe, Canada and Japan.

Obviously, in each Party, the domestic fusion research and development programme should allow for full and effective participation in ITER construction and operation in ways that

- assure the technical success of the project,
- ensure a permanent knowledge of the project available throughout the programme, and
- stimulate sustained interest to participate from home institutions.

9.3 Parallel Technical Work

During this period of approach to possible joint implementation, further technical work is still required to enable an efficient start of ITER construction when decided. It includes mainly:

- adaptation of the design to the characteristics of (a) potential site(s) and its (their) regulatory environment, and formal review of its completeness (a necessary step in QA);
- preparation of licensing applications by a closer (possibly formal) dialogue with the host regulators;
- continuation of physics R&D to take benefit from the further experimental results in present devices, and movement of the technology R&D towards more manufacturing R&D, except in ongoing development in a few specific areas, such as heating and current drive systems, and NbTi winding tests to confirm operational margins;
- preparation of technical specifications for procurement of hardware on the critical path of the construction schedule.

The Parties, in their exploratory discussions, are considering the new possible framework for their collaboration in technical work after July 2001 and after the end of the EDA Agreement validity. This framework should maintain the good coopertion between the Parties, enjoyed during the EDA phase, and provide for an organisation strong enough to keep coherence of the project, in front of requests for design changes linked to specific characteristics of potential sites. There would be a considerable advantage if the organisation for this phase already resembled that thought appropriate for ITER construction. The Explorers should take the full benefit from this interim period, to increase the confidence of outsiders in the Parties' capacity to build and operate a successful ITER.

10. Summary and Conclusions

- In 1999 a four Party Working Group concluded unanimously *"the world program is scientifically and technically ready to take the important ITER step*." [24]. The progress of the ITER EDA in the last two years combined with the continuing flow of scientific and technological data from existing experiments, sustain this view.

- The design of ITER which now meets the revised detailed objectives established in 1998 approaching the 50% cost saving target, still satisfies the overall programmatic objective of ITER .

- The lower costs of the new design make it possible for participants to benefit from the sharing of costs and the pooling of expertise that joint implementation allows, whilst maintaining a good balance in the domestic programme of each Party.

- The success of the joint activities among the ITER EDA Parties demonstrates the feasibility and underlines the continued desirability of aiming for a joint implementation of ITER in a broad-based international collaborative frame. The key tasks for the fusion community are now to confirm, within programme planning, the strategic priority to proceed with ITER in an international collaboration as the centrepiece of the world fusion energy development programme, to determine, with other potential participants, the overall terms of an international frame for joint construction and operation, and to prepare the necessary consequential adaptations of the programme organisation.

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