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Accelerated development of fusion power

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Accelerated Development of Fusion Power

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Executive Summary

Introduction

In the last decade there has been great progress in the plasma physics, materials science and technology of fusion power, which is now moving towards practical realisation. There is a clear path to the realisation of economic and environmentally attractive electrical power generation: the main technological requirements are known, and approaches to the resolution of the principal issues have been evolved and broadly accepted. It remains to assemble these activities into an integrated and focussed programme, implemented within an international framework and evolving from the present laboratory-based research to industrial exploitation. The urgent need to find global solutions to the provision of environmentally benign sources of power has led to a widespread acceptance of a 'fast track' approach to fusion development. This paper, which is a discussion document, proposes a 'fast track road map'. It provides an outline plan for fusion development, starting immediately and leading to one or more electricity-generating prototype power plants (DEMOs), connected to the grid, which can be directly followed by the construction of commercial fusion power plants. It could be of use to decision-makers, funding bodies and implementing organisations.

The programme outlined in this paper is not a *prediction* of what will occur. It is a description of what can be done, and what must be done, to make the accelerated development of fusion power actually happen. Effective implementation of the programme requires a change of culture in the fusion community to a project-oriented, "industrial", approach, accompanied of course by the necessary political backing and funding.

The entire cost of the fusion development programme outlined in this paper is equal to only a week or so of spending in the (three trillion Euro per year) international energy markets.

Present Status and Future Developments

The plasma physics, materials science and technology of fusion power have all reached the stage where the remaining development requirements can be readily envisaged, and the main research facilities and activities planned. In terms of major facilities, the essential next stage in the fast track development of fusion is the parallel construction and exploitation of the ITER tokamak and the International Fusion Materials Irradiation Facility (IFMIF), before the construction of the first electricity-producing DEMO plants. Commercial plants would directly follow the DEMO step. The burning fusion plasmas

and much of the technology required for DEMO and commercial plants will be tested by ITER, and IFMIF will test the materials.

The good prospects for fusion power have been confirmed by a comprehensive Power Plant Conceptual Study (PPCS), completed by the European Fusion Programme in 2004. This study developed four conceptual designs for power plants, and used them to assess the economic and environmental prospects of fusion power. Even the two near-term power plant conceptions showed that fusion has major safety and environmental advantages relative to current sources of baseload electricity and is likely to be economically competitive with other environmentally responsible sources of future electricity. The PPCS also sets the broad technical goals for the fusion programme, including those used in this Fast Track proposal.

The intermediate DEMO stage has not been much studied in recent years, although European and Japanese projects are currently starting. The completion of these studies will permit the revisiting and elaboration of the fast track road map using a ‘bottom up’ description of DEMO objectives and project cycle rather than the broader approach taken here.

In addition to the facilities so far mentioned (the ‘pillars’ of the fusion programme), the continuation of certain existing devices and the utilisation of a number of possible future ancillary devices and projects (‘buttresses’) is desirable. The buttresses optimise the project cycles of the pillars, reduce the overall risk, extend the available options and in some cases accelerate the programme.

Pillars

The main fast track requirements in relation to the pillars of the programme are:

- ITER: Construction to begin as soon as the siting issue is resolved. So this decision is required immediately. Exploitation to be accelerated by an optimised JET/JT-60 programme continuing until ITER commissioning. Prioritisation of ITER exploitation, including the Test Blanket Modules, in favour of DEMO relevance. Development of reliability data in Extended ITER;
- IFMIF: Immediate start on an accelerated IFMIF engineering design, construction and exploitation project. Prioritisation of IFMIF exploitation in favour of DEMO relevance;
- DEMO: Development of conceptual and then engineering designs in parallel with ITER and IFMIF construction and operation, so that the information from these projects is used to improve the designs. A flexible DEMO design that permits construction to begin before the details of in-vessel component design have been finalised. Start of first DEMO construction as soon as ITER/IFMIF information permits grant of construction and phase1 operation licences.

Buttresses

Only the main buttresses of the programme are listed:

- Existing and future satellite tokamaks. A single ITER has to address the main experimental issues in a serial manner. Some of the issues can be addressed earlier, or in parallel to ITER operations, in a cheaper satellite tokamak optimised for them, thus permitting the streamlining of the ITER experimental programme;

- Pre-IFMIF materials testing: The IFMIF testing programme requires a commitment to particular materials composition choices. A large risk reduction and small programme acceleration would result from the greatly increased use of multi-beam, fission and spallation sources, in conjunction with modelling, to optimise the IFMIF material choices;
- Component test facility: Risks would be reduced and options would be extended, if some of DEMO's tasks in optimising in-vessel components were achieved collaterally or earlier in a separate smaller machine. This is the function of a Component Test Facility (CTF). If this facility could be deployed early enough, a substantial acceleration in the overall programme might be achieved.

Risks and their Mitigation

There are of course a range of technical risks of delay and failure, and other risks that could affect timing, such as tritium availability. The risks foreseen are primarily risks of delays to the schedule or of reduction of the economic performance of the first generation of power plants. The role of the buttresses in reducing the risks is a key one. An even greater impact on risk would be achieved by building more than one IFMIF and several DEMOs, but this has not been assumed in the present road map scenario.

Alternative concepts

In parallel to the Fast Track elements of the fusion development programme it is desirable to devote a proportion (say 10%) of the overall programme to research into alternative and/or advanced plasma configurations and materials. As well as broadening understanding of fusion concepts, which has indirect benefit to the fast track, these lines of work may, at a later date, provide improved DEMOs, leading to improved commercial power plants.

Conclusions and Recommendations

The paper concludes that, in a reference Fast Track not utilising the buttresses, high availability operation of DEMO, confirming all the information needed for construction of the first commercial power plant, could occur thirty-seven years after the decision to go ahead with ITER and IFMIF. The first commercial plant would operate forty-three years after the decision to go ahead with ITER and IFMIF. Inclusion of the buttresses cuts four years from these dates.

The international nature of fusion development requires that agreement on the fast track road map is required from many parties. A change of culture is required, to a project-oriented 'industrial' approach, accompanied, of course, by the necessary political backing and funding. For the road map pillars the main requirements are:

- Operation of JET and JT-60 to prepare for ITER exploitation;
- Construction of ITER starting immediately;
- Optimised design and construction of IFMIF, starting immediately;

- Agreement on the main technological choices for the first DEMO;
- Prioritisation of the ITER and IFMIF programmes to support the first DEMO;
- Provisional engineering design of the first DEMO to be completed in advance of ITER and IFMIF results
- Construction of first DEMO as soon as licensing is possible.

For the buttresses: their role in maintaining, or accelerating the overall schedule and reducing risk is significant, so there is a strong incentive to include them in the international agreements required for the pillars.

Accelerated Development of Fusion Power

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Abstract

In the last decade there has been great progress in the plasma physics, materials science, and technology of fusion power, which is now moving towards practical realisation. Based on these developments, studies have demonstrated that an economically acceptable first generation of fusion power plants, with major safety and environmental advantages, could be accessed by a “fast track” route of fusion development, through ITER and without major materials advances. Thus the motive and opportunity for a fast track roadmap to fusion power are clear, and in general terms this idea is now well accepted [1–3]. More detailed development of such roadmaps is valuable for providing guidance to the future direction and prioritisation of fusion research and development. This note gives a discussion of the technical elements, and risks and benefits, of fast tracks to fusion power, and an initial development of the sequence of programme elements into a reference fast track and a variant.

1. Introduction

In the last decade there has been great progress in the plasma physics, materials, and technology of fusion power, which is now moving towards practical realisation. Based on these developments, extensive recent European studies [4–10] have been performed of conceptual designs of commercial fusion power plants, analyses of their safety, environmental impacts and economic characteristics, and analyses of the incorporation of fusion power into economic scenario modelling.

The results of the studies demonstrate the following points.

- Fusion has very well attested and attractive inherent safety and environmental advantages, to address global climate change and gain public acceptance [4,5,8,9].
- The cost of fusion electricity is likely to be comparable with that from other environmentally responsible sources of electricity generation [6,7,8,9].
- Economically acceptable first generation fusion power plants, with major safety and environmental advantages, could be accessed by a **“**fast track**”** route of fusion development, through ITER and IFMIF and without advanced modes of plasma operation or major materials advances (though optimisation and extensive testing of materials in power plant conditions will be essential) [8,9]. There is also potential for more advanced fusion power plants [8,9].
- Fusion, if deployed according to earlier, more conservative, plans for the rate at which it would be developed, could capture twenty percent of the European electricity market by the end of this century [6,10], or earlier if a “fast track” development were successful [6].

These conclusions are broadly in line with those of earlier studies elsewhere [11-16].

Overall, these results, together with the abundant availability of fusion fuels, show that fusion is an attractive option to contribute in the medium and long term to sustainable energy generation; it would be particularly suited to baseload electricity supply and would ideally complement renewable energy sources in a future energy mix.

The entire cost of the fusion development programme outlined in this paper is equal to only a week or so of spending in the (three trillion Euro per year) international energy markets. As a result, the expected discounted value of fusion development is substantially positive [17-18]: a successful fusion programme would massively over-recover the costs of its development.

Thus the motive and opportunity for a “Fast Track” roadmap to fusion power are clear, and in general terms this idea is now well–accepted [1-3]. More detailed development of such roadmaps is valuable for providing guidance to the future direction and prioritisation of fusion research and development. This note gives a discussion of the technical elements, and risks and benefits, of fast tracks to fusion power, and an initial development of the sequence of programme elements in a reference fast track and one variant, with brief comments on other possible variants.

It is assumed that the primary aim is to establish fusion as an energy option, and the objective is to reach this point in the shortest possible time. Accordingly, this paper is concerned only with the programme elements that are needed to develop quickly an economically viable first generation of commercial power plants, exemplifying the safety and environmental advantages of fusion power.

This restricted focus means that other very desirable programme elements, mainly aiming at later improved power plants, are not discussed. These elements are in the fields of alternative plasma confinement concepts and the development of advanced materials. It is important to maintain research in these fields, at the level of, say, ten percent of the overall fusion development programme, in parallel with the fast track programme.

The plan of the remainder of this document is as follows. Section 2 describes the technical target of fast track development. Section 3 outlines the outstanding technical issues to be resolved, and section 4 shows how these may be resolved by the key envisaged devices (ITER and IFMIF, leading to one or more DEMOs) – these are termed the “pillars” of the programme. Section 5 outlines the valuable contributions that could be made by subsidiary devices – these are termed the “buttresses” of the programme. Section 6 discusses the risks associated with fast track development, and their mitigation. Section 7 presents and argues for a reference fast track schedule, using the pillars only, and an augmented schedule also using the buttresses. Section 8 discusses briefly the role of industry, and section 9 draws some comparisons with other documents and studies. Annex A contains additional details on key issues for the development of materials and blankets, which are time-critical items in the development of fusion.

2. The technical targets of fast track development

Models of attractive first generation commercial fusion power plants have been provided by the results of the European Fusion Power Plant Conceptual Study (PPCS) [8-9,19] and ancillary studies. The four conceptual designs developed within PPCS aimed to be attractive in two senses: to display the safety and environmental advantages of fusion; to have acceptable economics. These aims were achieved, even for the two non-advanced designs (Model A and Model B): accordingly, the assumptions built in to these two non-advanced designs may be used as guides to the target technical parameters for the purposes of the fast track planning. These are summarised below, together with a brief discussion of the key points. Details, including a complete set of self-consistent plasma and plant parameters, and further discussion are given in the PPCS Report [9] and summarised in a recent paper [19].

The results of PPCS [8-9,19] showed that the safety and environmental advantages of fusion are well displayed in power plant designs based on the following:

- the blanket concepts that have been developed and tested for many years within the European fusion programme, and are to be tested in ITER; and
- the use of low-activation ferritic-martensitic steels that have been very successfully developed in recent years and are under characterisation within the European fusion programme.

It is clear, therefore, that these blanket designs and steels serve as good indications of the target technologies for the first generation of commercial power plants.

Turning now to economics, there are two components to the cost of electricity: internal (“direct”) costs and external costs. External costs are the costs of any adverse health effects or environmental harms arising from all stages in the generation of electricity by a technology. The PPCS analyses [8-9], based on extensive earlier European work [20], showed that the external costs of fusion electricity are very low, comparable to those of wind power and an order of magnitude lower than for fossil fuels. This very favourable result arises directly from the favourable safety and environmental characteristics of fusion power.

Consideration of internal costs raises a new set of issues, involving plasma physics as well as materials and technology. Extensive self-consistent parametric modelling supported by analysis [21], as well as the much more detailed systems and economic modelling and assessment within the PPCS [8-9], have shown that the variation of internal cost of electricity (coe) with the main parameters is well fitted by the following expression:

$$\mathrm{coe} \propto \left(\frac{1}{\mathrm{A}}\right)^{0.6} \frac{1}{\eta_{\mathrm{th}}{}^{0.5}} \frac{1}{\mathrm{P_e}{}^{0.4}\beta_{\mathrm{N}}{}^{0.4}\mathrm{N}^{0.3}} \qquad (1)$$

where, in descending order of relative importance to economics:

- A is the plant **availability**, which primarily depends upon the **lifetime** of the blankets and divertor, before they need to be replaced, and the **reliability of all the systems**, especially the in-vessel components;

- η_{th} is the thermodynamic efficiency, which primarily depends upon the **operating temperature and energy multiplication of the blanket**;
- P_e the net electrical output of the plant, which can be chosen;
- β_N is the normalised **plasma pressure**;
- N is the **ratio of the plasma density to the Greenwald density**.

It may be seen that there are no "show-stopping" target minimum values associated with any of these parameters, but they are all potential degraders of economic performance.

It may be seen also that failure to achieve higher values of one parameter can be offset by over-achievement in another, so only co-existent poor progress in several unrelated fields would markedly jeopardise economic performance.

In absolute terms, it has been shown [22] that a conservative power plant concept, based on the European blanket concepts referred to above, with plasma physics based on the conservative ITER design rules, would have an internal cost of electricity lower than the expected future performance of solar photovoltaic (PV), and similar to wind power if storage were necessary to produce power available on demand from this source. This could already be competitive in some countries, and would probably be more competitive in the future, as environmental constraints tighten.

However, a power plant based closely around the ITER parameters is not the most likely outcome of the fusion programme. For its non-advanced design conceptions (Models A and B), the PPCS [8,9] assumed some reasonable progress by ITER beyond its design assumptions, together with the above blankets. The plasma physics basis was assigned by a committee of European experts. Subject to these constraints, economically optimal designs were found, characterised by the self-consistent parameter sets summarised in the PPCS report [9,19].

These designs produce internal costs of electricity competitive with wind power without storage, and likely to be generally competitive in the future energy market [7-9,21,22]. The advanced PPCS designs (Models C and D, not discussed in this paper) illustrate the potential for improved economics in a second generation of fusion power plants.

Models A and B are identical in their assigned plasma physics constraints, of which the constraints on β_N and N are of primary significance (see equation 1). (The Models differ as a consequence of blanket and divertor performance.) Such parameter values have been attained in existing experiments. The plasma parameters of PPCS Models A and B [9,19] may be taken as indicative of the approximate quantitative targets for the likely most crucial technical plasma parameters of attractive first generation commercial fusion power plants.

Regarding the materials and technology parameters: the blanket and divertor parameters are those expected to be achieved by the blanket concepts being developed in the European fusion programme, together with divertor concepts using the same coolants. These blankets, apart from the crucial issue of lifetime in fusion neutrons, will be tested as modules in ITER. The structural material, reduced activation ferritic-martensitic steel (RAFM), for the first wall must withstand up to 15 MWy/m^2. Based on fission irradiations, promising candidate steels (Eurofer and oxide-dispersion-strengthened versions) exist – after optimisation these will be tested in IFMIF. Substantially lower irradiation damage will be experienced by blanket elements further from the plasma and by the divertor. However, the divertor armour will experience significant fluxes of both neutrons and plasma.

3. The Issues

The target will be reached with the resolution of all the outstanding problems that prevent the immediate implementation of commercial fusion power stations similar to the Models A or B described above. What are these problems? A list, summarising the issues that need to be addressed, follows. This has been structured in such a way as to bring out, in section 3, the roles and requirements of different devices.

- **Disruption avoidance** – disruptions, and other effects adversely influencing plasma stability and control, must be infrequent. Mitigated disruptions would not be a serious economic issue, but unmitigated disruptions should occur only a limited number of times in the plant lifetime;
- **Steady-state operation** - although not absolutely essential for a power plant, continuous plasma burn is economically desirable [23] and must be pursued;
- **Divertor performance** – several plasma physics, materials physics and engineering issues need to be addressed, including understanding of plasma/surface interactions, tolerance of or mitigation of transient heat fluxes, and engineering designs to remove heat efficiently;
- **Burning plasma** – ‘ignition’ is not necessary (or particularly desirable) for a power plant, but an energy multiplication (Q) above 10 (and preferably 20 - 30) must be achieved through sufficient plasma confinement and stability, and the physics of alpha particle heating, burning plasmas and control must be confirmed;
- **Power plant plasma performance** - in addition to the issues mentioned above, a beta comparable to that of Models A and B must be achieved (for economic performance) in a plasma in true power plant conditions without disruptions;
- **Tritium self-sufficiency** – tritium generation in blankets, tritium recovery and storage, and fuel cycle design, must be demonstrated;
- **Materials development** - materials must be optimised, particularly for plasma-facing components and structural components with good performance under irradiation;
- **Materials characterisation** - to allow engineering design, licensing and construction of a power plant (or any intermediate device), the materials must be characterised for these requirements, including the effects of neutron irradiation;
- **Plasma-facing surface lifetime** – there must be quantitative understanding of the effects of plasma/surface interactions, neutron radiation and heat loads, on all plasma-facing materials, and implications for their survival and need for replacement;
- **First wall/blanket materials lifetime** - the effects of neutron irradiation on structural and other materials, compatibility with coolants, and their ability to survive in the in-vessel environment must be understood to allow design optimisation and minimise maintenance outages;

- **First wall/blanket components lifetime** - the issues mentioned for the materials, above, must also be resolved for the complete fabricated components, including welding/joining technologies and the minimisation of component failure frequencies;
- **Divertor materials lifetime** - the same issues as mentioned for FW/blanket materials must be resolved, but in a different environment with different performance requirements;
- **Neutral beam and/or radio frequency heating and current drive** - these technologies must be developed for high reliability and at the scale required for a power plant;
- **Electricity generation at high availability** - all aspects of the plant systems must be developed to provide reliability, low failure frequency, short repair times, infrequent maintenance requirements, and rapid maintenance routines, leading to the power plant availability expected for Models A and B;
- **Superconducting machine** - the performance and reliability of superconductor magnets at the scale of a power plant, and the successful operation of a large superconducting machine, must be confirmed;
- **Tritium issues** – all aspects of tritium inventory control (retention, mobility, de-tritiation), especially in the torus, must be resolved.
- **Remote handling techniques –** these must be developed for efficient and speedy in-vessel replacement operations.

In parallel to the Fast Track development programme, further research into the most promising alternatives – stellarators and spherical tokamaks - to the main tokamak line of fusion development should be pursued together with research into advanced materials, as these lines may provide an improved second generation of commercial power plants.

4. Pillars of a Fast Track programme

The resolution of the issues listed above requires a programme of plasma physics, materials physics and technology research and development and engineering progress. This programme will be focused around the following key large experimental devices - the PILLARS of the fast track programme.

In the first stage of the programme the pillars are:

- **ITER** - assumed here to be as currently conceived, including its **Test Blanket Modules (TBMs)**, and to proceed to construction and operation without further delay;
- **IFMIF** - the non-plasma source of neutrons for the essential testing of materials in a high-energy neutron fluence, both to characterise their performance and to promote an understanding of materials behaviour;

In the second stage of the fast track, the pillar devices are:

- One or more **DEMO**s – each a power-plant sized tokamak that will from the start have a burning plasma configuration very close to that of a commercial power plant. DEMO will at a relatively early stage be capable of supplying electricity to the grid and be self-sufficient in tritium. Unless augmented by the earlier operation of a Component Test Facility (see section 5), the earliest phase (Phase 1) of DEMO operation will not display high availability, and may test a succession of concepts, e.g. for blanket and divertor design. At this point there will be a change of blankets and divertors (similar to what will occur at intervals in a commercial power plant) and DEMO will move on to a Phase 2 of higher availability that will demonstrate the commercial viability of fusion power;

ITER, the ITER TBMs, IFMIF and their roles are sufficiently well-known and studied to need no description in this section. Pertinent comments are made in section 7. However, DEMO concepts have not been much studied for many years (a European study is just about to begin); therefore the prime considerations are discussed below.

DEMOs

The requirements for DEMOs derive almost immediately from their roles in bridging the gap between the ITER/IFMIF (and their buttresses) generation of devices and the first generation of commercial power plants outlined above.

A DEMO must:

- Be based on, and must confirm in higher fusion power commercial size devices [9,19], the plasma physics basis developed by ITER (or by parallel devices for alternative concepts).
- Be based on the low-activation long-lifetime materials successfully tested in IFMIF.
- Demonstrate the safety and environmental advantages of fusion.

Very early in its operations, a DEMO must:

- Be essentially self-sufficient in tritium, based on full-scale versions of blanket concepts successfully tested in ITER.

By the end of its Phase 1 operations, a DEMO must:

- Confirm the armour lifetimes in simultaneous plasma and neutron fluxes**.** It is an unfortunate weakness in current conceptions of the fusion programme that this issue is not addressed by any part of the programme prior to DEMO. More thought should be given to making some earlier inroads into this problem.
- Provide information on the main problems of materials compatibility and reliability for blankets and divertors, so that more optimised components can be selected for Phase 2 operation.
- Desirably, be capable of supplying electricity to the grid. (This requirement is not necessary from the purely technical viewpoint.)

By the end of its Phase 2 operations, a DEMO must demonstrate confidence in:

- High reliability and availability, especially of optimised blankets, divertors, etc.;
- Long-term inter-compatibility of materials and components;
- Costing projections;

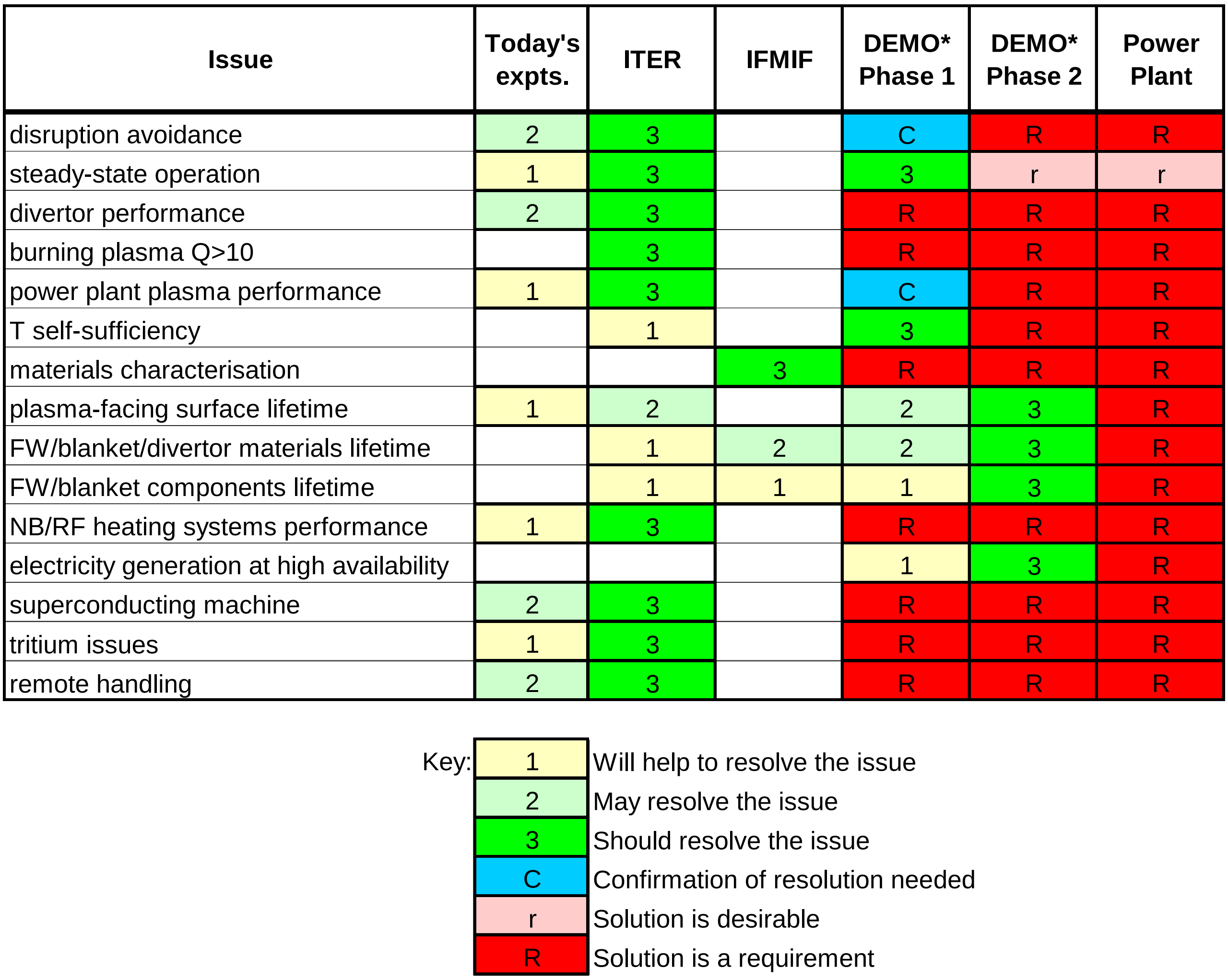
- Self-sufficiency in tritium; low tritium inventory.

Clearly the first DEMOs must have a conservative technology design capable of accepting a variety of candidate blanket (etc.) variants based on the same coolant choice, and some margins in the plasma operating regimes. Different DEMOs could be based on different coolants, fundamental blanket conceptions and plasma configurations. The parallel deployment of several DEMOs could reduce risks and expand design options for the commercial power plants.

To illustrate the role to be played by these components of the programme, Figure 1 displays the correspondence between the issues to be resolved and the ability of each of the pillar devices, together with existing facilities, to address it. A coding is used which distinguishes between the high expectation that a solution will be obtained (code 3) and the less certain possibility that it will (code 2). Also indicated are the areas where a facility will provide some assistance in resolving the issue (code 1) thereby bringing a final solution earlier. The requirements for problems to be solved to enable each stage are also indicated (code "R") with a different code ("r") where the requirement is less strong. The coding "C" indicates the confirmation in DEMO geometry of issues that will have been resolved for ITER.

Note that though materials development does not explicitly appear in Figure 1, this is an essential parallel activity throughout the programme. Testing and characterisation of the resulting materials are carried out in several of the facilities, as noted in Figure 1, and of course there is a strong coupling between this testing and the materials development programme.

There are other issues, for example the development of **plasma heating and current drive techniques**, which have not been included in figure 1, because they will necessarily be resolved in the course of pursuing solutions to the issues shown.



Issue	Today's expts.	ITER	IFMIF	DEMO* Phase 1	DEMO* Phase 2	Power Plant
disruption avoidance	2	3		C	R	R
steady-state operation	1	3		3	r	r
divertor performance	2	3		R	R	R
burning plasma Q>10		3		R	R	R
power plant plasma performance	1	3		C	R	R
T self-sufficiency		1		3	R	R
materials characterisation			3	R	R	R
plasma-facing surface lifetime	1	2		2	3	R
FW/blanket/divertor materials lifetime		1	2	2	3	R
FW/blanket components lifetime		1	1	1	3	R
NB/RF heating systems performance	1	3		R	R	R
electricity generation at high availability				1	3	R
superconducting machine	2	3		R	R	R
tritium issues	1	3		R	R	R
remote handling	2	3		R	R	R

Key:

1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
C	Confirmation of resolution needed
r	Solution is desirable
R	Solution is a requirement

* Risks would be reduced and options expanded by operating several alternative DEMO plants in parallel

Figure 1. Issues requiring resolution and how they are addressed by the pillar devices

In addition to addressing the specific technical issues, there is an imperative need to **create and maintain a coherent and fully international team with the individual and collective tacit knowledge required to operate ITER with minimal delay and confusion**. This is a key reason for operating JET, etc., until ITER operations commence. More generally, planning for the availability and deployment of trained manpower should be given greater attention. (A new European group has begun to examine the issue of the key skills.)

Finally, and of paramount importance, effective implementation of the programme requires a change of culture in the fusion community to a project-oriented, “industrial”, approach. In addition to the close integration of the ITER, IFMIF programmes and the programmes of the supporting devices, it would be highly desirable to create a top-level overarching steering board (e.g. chief scientific advisors to governments, supported by leading fusion experts) for developing fusion power, to keep the programme focussed on the fast track, avoiding unnecessary duplication and resisting the temptation to do interesting research not directly relevant to the objectives.

5. Buttresses of a Fast Track programme

By ‘buttresses’ of the fast track programme we mean ancillary, smaller, devices that would reduce risks, prevent the premature foreclosing of options, and provide acceleration of the programme.

In the first stage of the programme, JET and other current tokamaks (JT-60, ASDEX, DIII-D, etc.) can help to resolve plasma physics issues and some technology issues, or at least can accelerate their resolution on ITER.

The use of existing and projected facilities for materials irradiations, such as multi-ion-beam accelerators, spallation sources and nuclear fission reactors, closely coupled to the acceleration of modelling developments, should be able to speed up the understanding of materials behaviour and thereby:

- optimise the programme of tests on IFMIF, yielding the required results sooner;
- reduce the uncertainties, or imposed conservatism, in moving from the IFMIF results to the prediction of DEMO component behaviour.

Also in the first stage, two or more IFMIF devices in parallel would enable a wider spectrum of candidate materials to be tested in a timely way.

A satellite tokamak, not employing tritium, in parallel to ITER and ideally under the ITER management, could cost-effectively perform the exploration of plasma scenarios at minimal risk prior to their trial on ITER and/or could specialise in, for instance, steady state issues such as current drive. This would accelerate the resolution of such issues for ITER and for DEMO operation.

In the second stage of the programme, the operation in parallel of several DEMO devices, each with a different focus, would reduce the risks of the last stage in the development of commercial fusion power, and would allow the exploration of several technical options without imposing delays. It is increasingly accepted that, given that ITER and IFMIF have been successful, the most likely world fusion programme would include several DEMOs.

A specialised device, **CTF -** a Component Test Facility, much smaller than DEMO - could accelerate the progress in design and fabrication of in-vessel components, especially the growth of reliability, by testing them in fusion power-plant relevant conditions. A CTF would be a driven D-T device generating a sufficient flux of fusion neutrons over an area sufficient for the testing of components (rather than the small material specimens tested in IFMIF). It could provide, much more flexibly and cheaply than the first phase of DEMO, a facility for testing and improving designs for the critical in-vessel components, especially blankets, solving the main problems of materials compatibility and reliability. Such a device could have an important and cost-effective role in increasing the probability of rapid DEMO success and, if it could be deployed early enough, accelerating the DEMO programme. Further comments are given in section 7.

6. Programme risks and their mitigation

This section contains some discussion on the more significant programme risks and risk mitigation measures, and how these have been treated in developing the fast track plan outlined in the next section of this paper.

This is followed by a more general account of risk-adjusted economic valuation of more radically alternative fusion development scenarios.

During the development of the fast track sequences presented below, it became apparent that almost all the associated risks are risks of delays or (if the delay is not accepted) of having to back off somewhat from the economic performance of the first generation of commercial power plants (recall the discussion around equation 1).

There is a risk of failure to provide on schedule the required information from IFMIF (on the lifetime in fusion neutrons of well-performing materials), from the ITER TBMs (on blanket integration issues), or from the ITER plasma programme (on adequate plasma regimes with low plasma disruption potential, good steady-state characteristics, and adequate divertor lifetime). In most credible scenarios a few years delay for more R&D could rectify these deficiencies. Alternatively, depending on the urgency perceived, at that time, of developing fusion, it could be decided to press on immediately with a DEMO and accept a less economic first set of power plants, while continuing R&D in parallel to produce a more economically attractive second generation.

The buttresses, and measures such as in-parallel operation of two IFMIFs and several DEMOs, might produce some acceleration in the programme (which could be substantial in the case of an early Component Test Facility). However, the prime effect of including these ancillary devices is to reduce substantially the risk that the programme will be delayed or will produce an economically sub-optimal outcome. As can be seen from the general discussion below, the economic value of including the buttresses is substantial.

Commercial fusion power plants and DEMO must themselves generate at least as much tritium as they burn. ITER is not designed to re-generate the tritium that it will consume in the course of its operation, and a starting inventory of tritium will be required for the first DEMO. Existing and projected stocks of tritium, largely arising from the operation of CANDU-type fission plants, after allowing for natural decay, will be sufficient for the operation of ITER and, with a small margin, the start of DEMO. However, there is some risk of shortfalls in tritium availability should the programme be delayed, and this would be more acute in the context of a multi-DEMO programme. There are no technical obstacles to the production of tritium by research-reactor-size fission plants, but this is an avoidable expense that should be avoided – by proceeding apace with the fusion development programme.

As remarked in the introduction, the entire cost of the fusion development programme outlined in this paper is equal to only a week or so of spending in the international energy markets. As a result, calculations [17,18] using probabilistic decision theory and discounted cash-flow analysis have shown that on any reasonable assumptions the risk-adjusted (expectation value) net present value of fusion R&D is substantially positive: the discounted expected benefits greatly exceed the discounted expected costs of development. Based on the main features of these calculations, some conclusions may be drawn on more radically variant development scenarios.

- A slower rate of development would reduce the risks, but would also reduce the risk-adjusted net present value, since it would delay the benefit.
- Speeding up the programme, by overlapping of the stages, would increase the risk, but would nevertheless increase the risk-adjusted net present value.
- Reducing the risks by spending more, even much more, for example by having several IFMIFs in parallel in the first stage of the programme and several DEMOs in parallel in the second stage of the programme, would increase the risk-adjusted net present value.
- Speeding up the programme at constant risk, by combining overlapping of stages with parallel DEMOs (etc.), would probably increase the risk-adjusted net present value.

In summary, these studies indicate that a radically greater rate of expenditure on fusion development would probably be economically justified, now that the programme is making the transition from the research to the development phase. Nevertheless this is not assumed in the scenarios presented in this paper.

7. The sequence of the elements of Fast Track programmes

In this section, the considerations in the earlier sections are used to construct two fast track fusion development sequences – a reference sequence involving only the “Pillars”, and a variant involving both the “Pillars” and the “Buttresses”.

All elements of the programme carry risks of failure, risks that are difficult to quantify. To minimise the overall development risk, all elements should be commenced as early as possible. This is necessary even if they are not on the critical path to the target of viable fusion power, since delays may put them on the critical path. Risks may be reduced, and options extended, by parallel developments, for example several IFMIFs to more rapidly test a range of materials and several DEMO devices based on a range of promising design concepts, including spherical tokamak and stellarator as well as conventional tokamak concepts.

Design, construction and operation of every device listed should commence as soon as the requirements are met. Specifically:

- **JET** and other existing devices (JT60, ASDEX, DIIID, etc.) - programmes targeted at the fast track approach should be devised and started without delay, including the implementation of any required upgrades; in addition, for JET, the maintenance of a competent team ready to operate ITER is a key contribution to the fast track;
- **Multi-ion-beam, etc.** - the possibilities of exploiting existing and planned facilities for materials research should be pursued immediately;

- **ITER** - a decision is needed as soon as possible, and the experimental programme for ITER should be optimised to provide as early as possible those results needed for DEMO design and construction;
- **IFMIF** - not being dependent on any other development, engineering design and construction should proceed as soon as possible on the timescale recently proposed by EFDA [24]; ideally, several IFMIFs should be constructed and operated in parallel. The testing programme of IFMIF(s) should be prioritised to produce as early as possible the essential information for DEMO design;
- **DEMO** - **design** work for DEMO should commence immediately, even though revisions will be inevitable as the programme proceeds; **construction** should commence as soon as the design has reached a point that there is confidence that it can achieve its objectives. A design incorporating some conservatisms, that permits some flexibility in the operating configurations is desirable, even if this means that DEMO may be somewhat sub-optimal. If several alternative DEMOs are constructed in parallel, a greater risk for each DEMO could be accepted, allowing an earlier start to construction. Though DEMO and its blankets will be based on near-term materials, DEMO will have test blanket modules based on advanced materials, aiming at the second generation of commercial power plants;
- **CTF** - like DEMO, **design** can commence immediately, and will then be subject to continual modification. Because the requirements for CTF are (on balance) *less* than those for DEMO (as figure 1 shows), it should be possible, at some risk, to commence **construction and operation** of CTF before that of DEMO;
- **Power Plant - design** concepts can be started immediately and updated as the programme develops; **construction** should be possible as soon as the final requirements are satisfied by DEMO and/or CTF, or conceivably by several different DEMOs.

These considerations are developed into a reference sequence, incorporating the pillars only, illustrated in Figure 2, and a variant sequence, incorporating the buttresses also, illustrated in Figure 3. The sequences in Figures 2 and 3 are only indicative, and are based on:

- the assumption of no delays caused by decision-making, and
- the judgements summarised in the points set out below regarding the key technical points. These judgements reflect discussions within working groups set up for this purpose within the EURATOM/UKAEA Fusion Association.

The zero of time in these figures is 2005 (calendar years are also indicated, on the lower of the two time bars). 2005 has been assumed as the year of the firm decision to go ahead with ITER, with agreement on siting, finance and top management. To avoid excessive cross-referencing and repetition, the summaries in the numbered points below refer only to the roles played by the pillars, with the roles of the buttresses discussed in the subsequent unnumbered paragraphs. The red and green lines in figures 2 and 3 illustrate key flows of information and experience between different projects. They are taken to be at the estimated times at which enough information will have accumulated to give sufficient confidence in proceeding with the indicated stage of design, licensing, construction or operation of DEMO or a commercial power plant. The ***green (dashed) vertical arrows*** illustrate information flows that are expected to be confirmatory of the assumptions that went into the design processes. The ***red (solid) vertical arrows*** illustrate information flows needed at earlier stages of the design of plant (or operational planning).

Figure 2 also displays the parallel research programme on alternative concepts and advanced materials. *Solely for reasons of space*, this is not shown in Figure 3.

Plasma physics and plasma engineering

1. A period of two years has been allowed, after the ITER go-ahead decision, for mobilisation, review and licensing. Thereafter, construction will proceed as currently planned. Thus operations begin after ten years.

2. ITER plasma physics and plasma engineering activities should be a top-down-directed programme aiming at providing as early as possible the key inputs for DEMO. It must be firmly focussed on providing as early as possible the crucial confirmation of reliable "good enough" plasma regimes for a DEMO based on near-term plasma physics (see section 2), rather than going for "peak performance".

3. In contrast to current plans, the experimental plan for the first decade of operations should move from the H&D mode more rapidly, and the time saved should be transferred to the phase of high duty DT operation.

4. The investigation of issues relating to plasma-materials interactions, especially divertor issues, should receive priority.

5. As a result of such increased prioritisation and focus, sufficient information will be available from ITER plasma physics and plasma engineering experience (primarily on plasma regimes, divertor operation and plasma – materials interactions) by the eighth year of its operation to give confidence in proceeding with the construction of the first DEMO.

Thereafter, an extended period of ITER operation will provide information on plasma regime optimisation for improved economics of power plants, and will show how to improve the reliability of systems. This information will be important input to the conceptual design phase of the first commercial power plants.

In the variant scenario (Figure 3), the satellite tokamak will be used to accelerate the progress of ITER plasma physics studies, by performing scoping studies in a low-risk environment. This will reduce the risk of failing to provide on time the flow of confirmatory information at 5 above.

Blanket optimisation and testing

1. In accordance with current planning, the ITER test blanket modules (TBMs) will be deployed near the very beginning of ITER operations.

2. It is not possible to reproduce in the ITER TBMs the geometry and loading conditions of DEMO blankets. Therefore, as explained in Annex A, the TBMs and their testing have to be designed to provide validation data for the DEMO blanket design models, so that design calculations for the DEMO Phase 1 blankets are performed with the smallest possible extrapolation from a known basis.

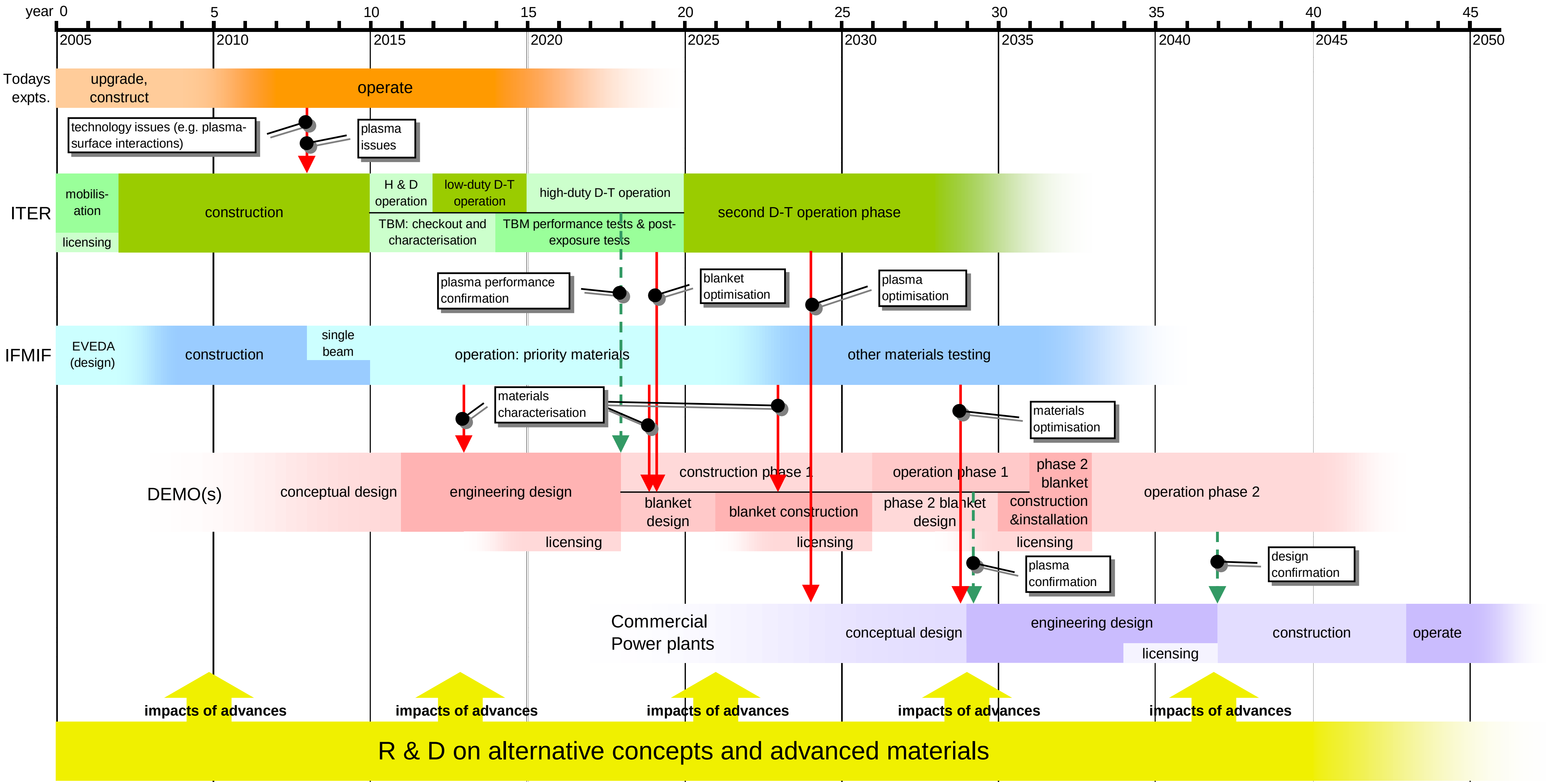


Figure 2. Possible sequence of existing and pillar devices in the reference Fast Track programme.

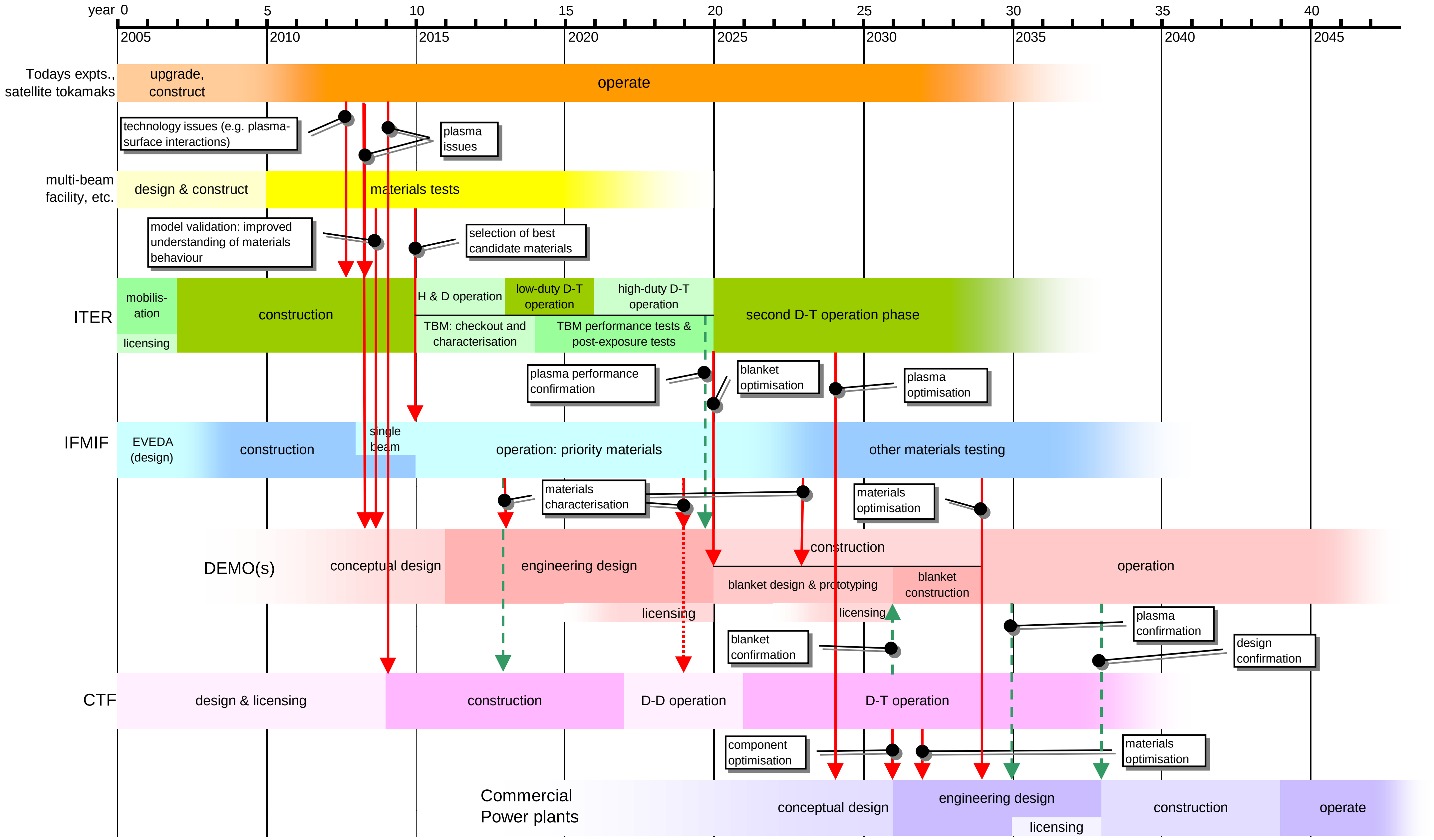


Figure 3. Possible sequence of existing, pillar and buttress devices in the variant Fast Track programme.

3. Unlike present plans, the ITER TBMs should be run as a top-down-directed programme focussed on DEMO, along the lines described in Annex A. The testing plan must initially be exclusively focussed on the crucial near-term blanket candidates for DEMO Phase 1, with low activation ferritic-martensitic steel or oxide-dispersion – strengthened steel as the structural material. Sufficiently early operation of ITER in DT mode (see above) is another requirement.
4. If the programme is thus prioritised and focussed, sufficient information should be available, from post-exposure testing of the TBMs, before the ninth year of ITER operation to warrant the finalising of DEMO Phase 1 blanket design and, shortly thereafter, the start of Phase 1 blanket construction.

Materials optimisation and testing

1. As indicated in a recent EFDA paper [24], the design and construction of IFMIF can be sharply accelerated, compared to the earlier severely resource-constrained plans, by giving IFMIF the greater priority and resources that it urgently needs. Thus IFMIF and ITER begin operations at the same time, and operation with one IFMIF beam begins two years earlier.
2. In addition, however, the present plans for the IFMIF testing programme need to be revised, as indicated below and further discussed in Annex A, so as to give priority to fast track imperatives.
3. Contrary to present plans, IFMIF should have a top-down-directed programme: the testing plan must initially be firmly focussed on the crucial near-term structural material candidates for DEMO. Unless there are two IFMIF's, either a development of the low-activation ferritic-martensitic steel, EUROFER, or an oxide-dispersion-strengthened variant (ODS), must be tested first and used in (the first) DEMO blankets and divertors, leaving the testing of other materials and advanced material possibilities to a later stage.
4. It is judged also that it is unnecessary to test in IFMIF the ITER Test Blanket Module materials prior to their deployment in ITER. The currently-planned "first phase" of very low fluence exploratory IFMIF testing, if it is desired, can accordingly be reduced to the period of single beam operation.
5. The permanent components of DEMO (the shield and components further from the burning plasma) will experience only low levels of (substantially thermalised) neutron fluence. Materials for these roles therefore only need a relatively low level of exposure in IFMIF (followed by post-irradiation examination). Sufficient information for the purposes of DEMO design and licensing, for these components, will be available by three years after the beginning of full IFMIF operation (one year of full exposure plus two years of post-irradiation analysis).
6. Since the first phase of the first DEMO will have low reliability, hence low availability, the first set of DEMO blankets and divertors will only experience neutron fluences of order 3-4 MWy/m^2 (equivalent to 30-40 dpa in steels). The corresponding materials therefore only need exposure in IFMIF to these limited levels, in order to validate design for Phase 1 of DEMO: however, some additional exposure would be prudent. Accordingly, ample information will be available, from the post-irradiation examination of specimens from IFMIF, to warrant DEMO first blanket and divertor construction by the eighth to ninth year of full IFMIF operation.

7. Exposure to 150 dpa, which will require ten years of IFMIF operation plus about three years of post-irradiation examination, will be required for the testing of materials for the DEMO Phase 2 blankets. Accordingly, sufficient information will be available from the post-irradiation examination of specimens from IFMIF to warrant DEMO Phase 2 blanket and divertor design by about the thirteenth year of full IFMIF operation. This is three years earlier than required according to figure 2.

Thereafter, testing on IFMIF can contribute to the optimisation of materials for the first commercial power plants.

In the variant scenario (Figure 3), the choice between optimised Eurofer and ODS, for the first phase of IFMIF testing, should be made, and the testing plan of IFMIF might be accelerated, by the use of multi-ion-beams, spallation sources and other facilities to validate understanding and predictive modelling capabilities. Thus the risk of making a sub-optimal choice of structural material will be reduced. Additionally, this will reduce the risk of failing to provide on time the flow of information at 5, 6 and 7 above.

The operation in parallel of two IFMIFs would enable simultaneous testing of the two prime candidate structural materials, thus avoiding foreclosing the options without delaying the programme.

Final integration and reliability development

1. Being based on some conservatism, the first DEMO can be licensed on the basis of the information provided by ITER, IFMIF and the use of validated understanding and modelling to extrapolate from ITER and IFMIF results. (This judgement is based on advice from expert consultants.)
2. In its Phase 1 operation, the first DEMO will confirm, in the larger geometry of a commercial power plant, the plasma physics basis developed by ITER, and will provide the technology basis for the design of the more reliable and optimised in-vessel components of the second Phase of DEMO.
3. Thus all information needed for the initiation of the detailed design of the commercial plant will be available by about the fourth year of DEMO operation.
4. Establishment of the reliability of ex-vessel components, for DEMO and the commercial power plant, can be performed in the extended ITER programme and in parallel programmes.
5. In its Phase 2 operation, DEMO should soon reach high availability operation with the chosen blanket. Accordingly, sufficient information to confirm the design, and initiate the construction, of the commercial plant would become available by about the eleventh year from the start of DEMO operation.

It can be seen from Figure 2 that, with these indicative timings, high availability operation of DEMO, and confirmation of the design of the first commercial power plant, are reached after about 37 years. Operation of the first commercial power plant begins after about 43 years.

In the **variant scenario** (Figure 3), the more rapid achievement of in-vessel (primarily blanket) component reliability, and the widening and optimization of blanket choice, is promoted by the deployment of a CTF. Several technical options for a CTF have been considered in the literature [e.g. 25-33]. The tokamak based CTF options [30-33] are suitable for component assembly testing and are envisaged here as forming the basis of the CTF buttress in Fig 3 (though it is the CTF's functionality rather than details of the underlying device that is key to its Fast Track role). With some risk, it is judged that D-T operation of such a CTF could commence in year twenty-one, allowing for adequate design time and input from near-term devices. The tokamak CTF options are relatively small (especially the spherical tokamak option) thus permitting low tritium consumption, with the possibility of not needing to self-generate tritium. A simplified licensing basis can also be envisaged: especially for the spherical tokamak option, the inventories of free energy and of hazardous materials, and the physical size of the device, would be small enough to allow licensing on the basis of inventories and ex-vessel containment provisions alone. All safety-critical components and structures would be well-shielded, so their conservative design would be confirmed by the same, very low fluence, inputs from IFMIF as are used to validate the permanent components of DEMO (year thirteen). If, which seems unlikely, information on in-vessel materials proved to be required from IFMIF, this would be available in year nineteen, as for the DEMO Phase 1 blankets above. In this eventuality the design and D-D operation of CTF should not be delayed: if necessary, replacement of the first wall and any other high fluence elements with materials proven in IFMIF could be made before full D-T operation begins.

In this scenario, Phase 1 of DEMO could be omitted. Finalization of the overall DEMO design parameters could be delayed by two years, enabling the design to be based on possibly more optimized plasma scenarios and Test Blanket Module results from ITER. High availability DEMO operation would begin four years earlier than in the reference fast track, after thirty-three years, and operation of the first commercial power plant also would begin four years earlier, after thirty-nine years.

In the event that the CTF could not be deployed as rapidly as assessed above, the programme would revert to the reference fast track, with the CTF playing (at minimal cost) some of the roles of a parallel DEMO (see below).

The operation of several DEMOs, for example using different blanket conceptions and/or plasma operation scenarios, would widen, and promote the optimizing of, choices for the design of the first commercial power plant, without delaying the programme.

8. The role of industry

Fusion development has now reached the point at which the increased, and much more closely coupled, involvement of industry is crucial. In the context of the programme outlined in this paper, initial thoughts on the role of industry may be summarised as follows.

- The vast majority of ITER construction activities will be by industry. This volume of industrial orders is an order of magnitude greater than industry has so far contributed to the ITER programme. Industrial involvement must continue in other ways.
- Industry will require fusion laboratory collaboration in drafting tenders, especially in avoiding the underestimation of technical risk.

- It is very “important to harness the energies of individuals within the industrial communities …to assist in managing all phases of the programme” [1]. This is so at all levels including the very highest.
- Beyond ITER construction, and particularly in DEMO, industry must be involved in design and integration activities at a much earlier stage than in the past, with a fluid structure of staffing the projects.
- From the point of DEMO construction, execution of the fusion development programme will become predominantly industrial, though still with a significant research engineering component.

Much more thought needs to be given to these issues.

9. Overall milestones and comparisons with other studies

It is important to be able to explain the fast track in terms of milestones formulated to be meaningful to people other than fusion experts. For this purpose we have drawn upon the milestones appearing in the report of the European fusion fast track committee [1] and the recent UK Energy White Paper [34]. Table 1 below shows a suggested set of such milestones, the technical equivalents, and dates of achievement according to the reference (pillars only) fast track, Figure 2.

The King Report [1] gives 20-30 years for the achievement of the fifth milestone in Table 1: it gives no time scale for the achievement of the eighth milestone, but it is believed that 25-30 years was in mind. The UK Energy White Paper [34] gives 15 years, 25 years, 30 years and 50 years, respectively for the achievement of milestones 4, 5, 10 and 12. The reference fast track of the present note gives rise to generally similar or rather earlier dates. The variant fast track (Figure 3) is overall four years earlier still.

Table 1. Milestones in non-technical language and their achievement

Milestone	Year	Technical event
1. First plasma in ITER.	10	ITER hydrogen and deuterium operation.
2. Full operation of IFMIF.	10	Two-beam operation of IFMIF
3. Sustained fusion power at power plant levels.	17	7 years into ITER operation (several hundred MW).
4. “Nuclear fusion will be at an advanced stage of research and development” [34].	17	7 years of ITER and IFMIF operation.
5. “Demonstrate the technical feasibility of fusion power” [1] [34].	17	7 years of ITER and IFMIF operation.
6. Operation of a demonstration power station.	26	Operation of DEMO.
7. 1 GW electric power.	26	Operation of DEMO.
8. “A credible prototype for a power-producing fusion reactor, although in itself not fully technically and economically optimised” [1].	26	Operation of DEMO.
9. Export significant electricity to the grid.	33	Second phase of DEMO.
10. “Full scale power generation” [34].	33	Second phase of DEMO.
11. Establish fusion as an energy option.	37	High availability operation of DEMO.
12. “Commercially viable production of clean, safe and renewable energy without the emission of greenhouse gases” [34].	43	Operation of the first commercial power plant.

The overall time scale of the reference (pillars only) fast track given in Figure 2 above is close to that of the “accelerated schedule” road map of Lackner et al. [35]. There are differences in detail but only differences of a few years in the main elements. Lackner et al. do not consider the role of the buttresses. There is strong overlap in the most important requirements of fast track development. In both studies the near term requirements are the early construction of ITER and IFMIF and the elimination of delays due to decision making. Both studies also emphasise the need to begin DEMO design as soon as possible, and the need for supporting work in parallel to ITER construction and operation.

Comparisons with the fast track of the USA FESAC report [3] are made difficult by two factors:

- The intention of the FESAC authors to undertake the entire development, apart from ITER and IFMIF, within the USA; and by
- The parallel development in that fast track of inertial fusion energy, up to a decision point between these in 2019.

The overall timescale is not so different, but there are significant differences in aims and in the roles of devices. In the FESAC fast track:

- The economic target is more ambitious regarding internal costs, whilst ignoring the role of external costs. For this reason the first generation of commercial power plants, and so also DEMO, are intended to be more advanced in their plasma regimes and materials.
- Accordingly, both "Concept development" and a CTF have central roles: in effect they are pillars of the FESAC programme.

10. Concluding remarks

The programme outlined in this paper is not a *prediction* of what will occur. It is a description of what is technically possible, and must be done to make the accelerated development of fusion power actually happen. It requires agreement, commitment, funding and not too many unpleasant surprises. The funding required is modest compared to the expected benefits of fusion power, and is equal to only a week or so of spending in the international energy markets. The measures needed for implementation of the programme are beyond the scope of this paper, but it is noted that effective implementation will require a culture change in the fusion community to a project-oriented, 'industrial', approach.

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ANNEX A

Blanket and Materials Technology for DEMO

1. INTRODUCTION

The construction of a schedule for the Fast Track approach to fusion includes as one of its more time-critical elements the development and testing of the materials and components required for the DEMO first wall, blanket and divertor. These components will be subjected to neutron fluxes and fluences and to surface heat loads at power plant levels. So this line of fusion power R&D has to provide the necessary DEMO design information for these irradiation conditions, validated by experiment so that design calculations for the DEMO Phase 1 blankets can be performed with modest extrapolation from a known basis. The effects of surface heat flux are addressed by the ITER project. This annex addresses blanket technology and the neutron-induced irradiation damage to structural materials.

No recent study of DEMO is available to provide a definite set of targets for the development programme. Table 1 gives the assumptions made in substitution for design targets:

Table 1. DEMO power density and irradiation damage parameters

First wall source neutron power density	Mean: 2 - 3 MW/m^2 Max: 2.8 - 4.2 MW/m^2	These parameters are approximately 5 times ITER values
Neutron-induced displacement damage limit	80 - 150 dpa	For the purpose of estimating IFMIF irradiation times, the upper end of this range is assumed
Main structural material	Ferritic-martensitic steel *or* Oxide Dispersion Strengthened Steel (ODS)	Base structure of first wall and divertor, breeding blanket and cooling tubes

In addition some options for DEMO remain open:

- Choice of coolant: water, gas or liquid metal;
- Choice of surface and heat sink materials for the first wall and divertor;
- Choice of tritium-generating and neutron multiplier materials;
- Choice of joining technologies (welding, diffusion bonding etc.).

In the European approach to DEMO construction, these materials and technological issues are addressed in two separate programmes, namely:

- **ITER Test Blanket Module (TBM) Programme.** Conceptual DEMO blanket designs have been adapted to provide sets of test modules which can be irradiated in ITER equatorial ports. The neutron fluence available is insignificant, so lifetime issues are not tested;
- **IFMIF Irradiation Programme.** IFMIF provides DEMO neutron fluences in a pseudo-fusion spectrum, for the irradiation of small materials samples.

This Annex sets out to describe the earlier-proposed objectives, modes of implementation and schedules of these programmes, and then the feasible modifications to them to satisfy fast track requirements.

2. ITER TEST BLANKET MODULES

Three equatorial ports in ITER (nos. 2, 16 & 18), with a combined first wall area of 10.4 m^2, are dedicated to the Test Blanket Module (TBM) programme, and are available at all stages of operation. At its nominal operating power of 500MW (fusion power) the peak value of the neutron wall load is 0.78 MW/m^2, which is about 20% of the assumed DEMO value. It follows that all neutron-induced reaction rates are ~20% of DEMO values, including volumetric nuclear heating. (The accumulated neutron damage effects in ITER are much lower still than in DEMO because of the much lower integrated neutron fluence in ITER). Therefore the full and simultaneous replication of DEMO neutron-*flux* related effects is impossible in ITER, and the irradiation programme has to synthesise relevant results from a number of separate tests and then extrapolate to DEMO conditions. The ITER and DEMO electromagnetic field strengths, and hence the stresses they induce, are similar. However the pulsed nature of ITER gives rise to problems absent in DEMO, namely fatigue arising from the varying stresses of electromagnetic and thermal origin.

For the 2001 ITER report, Europe, Japan and the Russian Federation each produced TBM designs, two in each case [A1]. [Since that time the United States has begun the process of producing TBM designs.] No attempt was made at that time to co-ordinate the design efforts or to deliberately consider complementary systems, and it was assumed that ITER would be used as a 'user facility' for the irradiation of each parties' test modules. However an exercise was undertaken to design a common frame for one of the ports, accommodating the European helium-cooled pebble bed and Japanese helium-cooled solid breeder modules simultaneously.

Even in a fast track approach it will not always be possible to achieve full interaction between the ITER TBM and IFMIF irradiation programmes on the requisite time-scale, so that the end results for DEMO may not be fully self-consistent. In other words, the DEMO material tested by IFMIF may not be identical to the DEMO material used in the corresponding TBMs.

The information used in this section is taken from the July 2001 ITER Final Design Report [A1].

2.1 Objectives

The performance parameters to be tested in the TBM programme are:

Tritium generation ratio: demonstration that in start-of-life conditions the tritium generation ratio is sufficiently above unity to ensure a closed fuel cycle. The burn-up of tritium generating and neutron multiplying materials occurring in DEMO cannot be replicated in ITER;

On-line tritium extraction: the release of tritium from the generating materials and removal in purge circuits, and demonstration that hold-up in, and permeation through, barriers does not cause unacceptable losses or contamination of coolant streams;

High-grade heat production: demonstration that the outlet temperature is sufficient for efficient electricity production, while maintaining all parts of the blanket within specified operating parameters, including temperatures, erosion and corrosion rates;

Structural integrity: demonstration that the module structure can tolerate the electromagnetic, thermal and load stresses, including the temporal component and lifetime integrity (in the absence of significant irradiation damage).

The degree to which the test module programme can meet these objectives by direct experimental measurement varies from one parameter to another. **However a common aim is to provide validation data for the design models, so that the design calculations for DEMO are performed with the smallest possible extrapolation from a known basis.**

2.2 Currently Planned Programme

The six TBM design concepts presented in the ITER FDR [since augmented by two USA design concepts] include a range of structural, neutron multiplying and tritium-generating materials and coolant types, representing a spectrum of near- and long-term options. The present planning assumption is that the modules will each be allocated a test port (each of the three available ports can accommodate two modules), so that the test programmes proceed simultaneously. From the operational viewpoint this has advantages. In particular it permits the designation of coolants to ports, so that the external sections of the coolant and tritium purge loops can be considered as permanent. It also allows the test programmes to develop in line with the expected steady increase in ITER power and pulse length. The electromagnetic responses can be tested first during the H-H operating phase, since to first order they depend on the presence of fields but not reacting plasmas. Later testing of the other performance parameters would benefit from a gradual increase in the available surface power densities and neutron fluxes and fluences, and inevitably the TBM experimental programme must be adapted to the D-D, low-duty D-T and high duty D-T phases of ITER operation.

The low power density of ITER has led to various strategies for conducting the tests and developing the concepts. A common assumption is that the ten years of ITER Phase 1 operation are available for the tests. The estimate of the duration of post-irradiation testing is two years.

2.3 Fast Track Recommendations

A sufficiently imperative fast track approach dictates the dedication of as many port locations as necessary for the testing of the leading near-term candidate technology for DEMO. Furthermore, decision-making in the ITER TBM and IFMIF projects would require co-ordination, so that similar (preferably identical) structural and tritium-generating materials are given precedence in both programmes. Almost certainly, the structural material would be RAFM (Reduced Activation Ferritic-Martensitic Steel) or ODS (Oxide Dispersion Strengthened Steel), and the coolant would be water or helium, but the choice would have to be made within an international context; i.e. DEMO materials would have to be agreed by all ITER and IFMIF parties.

Examination of the reasoning underlying the currently-planned test schedules, but now with the restriction to near-term material choices described above (together with the likely constraint of only one coolant choice per port), shows that it would be possible to accelerate the testing schedule by six years. It would thus occupy four years rather than ten. This removes the ITER TBMs from the critical path, so in practice more testing time – up to six years - would be possible. The time-scales for the ITER FDR and Fast Track options are given in table 2. The post-irradiation allowance of three years includes one year for adaptation of the design codes in the light of the TBM programme conclusions, and subsequent modification of the DEMO design. Obviously, a further assumption is the pre-existence of an engineering design for DEMO, together with a preliminary negotiated position with the relevant regulatory body, so that the three-year post-irradiation period is confined to relatively minor modifications and to design validation. Ideally the DEMO design should be completed before the start of the ITER operating programme, since the TBM design derives from it.

Table 2: Outline schedule for ITER TBM programme

	Currently planned schedule (years)	**Fast track schedule (years)**
ITER first plasma	10	10
TBM irradiation programme	10	4 - 6
Post irradiation testing and DEMO design adaptation	3	3
Total	23	17 - 19

It should be emphasised that the fast track option depends crucially on sufficiently early operation of ITER in D-T mode.

3. IFMIF MATERIALS TESTING PROGRAMME

At full power the IFMIF test volume provides estimated displacement rates (in steel) and volumes as given in table 3:

Table 3. IFMIF irradiation capacity

Volume (litre)	Irradiation fluence (dpa/fpy)	Time to 150dpa at 70% availability (years)
0.1	> 50	4.3
0.5	> 20	10.7
6.0	> 1	-

These irradiation conditions are available only in phase 2 of IFMIF operation when two accelerators are focussed on the target. Non-fast-track outline plans for the irradiation programme were made during the Conceptual Design Activities (CDA) [A2] and updated during the Key Element Technology Phase (KEP) activities [A3]. In addition to the irradiation of the leading candidate steels for DEMO, it was planned to test the longer-term structural materials, namely vanadium alloys and SiC/SiC. The structural materials would occupy the highest flux region of the irradiation volume.

Like the ITER test blanket ports, IFMIF was, in the earlier (and still not superseded) plans of the IFMIF project, envisaged purely as a user facility with national materials laboratories supplying specimens, and post-irradiation testing conducted partly at the IFMIF site and partly at the home laboratories. However the volume constraint on the size of the test matrix necessitates international agreement on the specification of the materials to be tested; for instance, one grade of RAFM steel has to be agreed by all parties.

This Annex focusses on the testing of the main structural materials and weldments. However the IFMIF programme also includes the irradiation of lithium ceramics, insulating and barrier materials, beryllium, and first wall materials, mainly in the medium and low flux test modules. It is assumed here that all of this work can be completed on the time scale of the structural materials testing programme.

3.1 Objectives

The overall aim of qualifying fusion materials subjected to irradiation damage in DEMO and power plants was planned to be addressed in two phases (See ref. [A3] for full objectives). Phase 1, employing one accelerator, was intended to be devoted to a screening programme to optimise the selection of materials for the full power (two accelerator) phase 2. As well as steels, advanced materials (V alloys and SiC/SiC) and lithium ceramics would be tested, and comparisons with fission and spallation source irradiations would be made to determine the extent to which these could supplement IFMIF testing. Performance testing of candidate ITER TBM materials was also planned, although it is unlikely that this is required.

In phase 2, irradiations of the selected materials will be continued to levels of 50, 100 and 150 dpa, and studies of advanced structural materials, breeder ceramics and neutron multipliers would be completed.

3.2 Currently Planned Programme

The irradiation programme is highly constrained by the available high-flux volume, taken here to be the > 20dpa/fpy region of 0.5 litre. The test matrix must allow for evaluation of the principal engineering properties, and does this by the use of tensile, dynamic fatigue, fracture toughness, crack growth, charpy and creep specimens, and by the inclusion of TEM disks. To cover the need for specimen multiplicity and parameter ranges (strain rates, temperatures, creep pressures), a total of 72 specimens were proposed for each condition (temperature and dose) of each material. This batch of specimens occupies 38 cm^3, including the specimen containers. Optimisation of the high flux test module was reported to allow the simultaneous irradiation of 970 specimens in the high flux module [A4]. Thus 13 conditions can be tested simultaneously. The structural material programme currently proposed by the IFMIF team [A3] is summarised in table 4.

Table 4. Numbers of Irradiation Conditions for Testing in the IFMIF Structural Materials Programme Currently Proposed by the IFMIF Team

Material	Temperature levels	Dose levels	Conditions
RAFM	3	3	9
RAFM weldments	3	3	9
ODS	2	3	6
ODS weldments	2	3	6
Vanadium 1	3	3	9
Vanadium 2	3	3	9
Vanadium 3	3	3	9
SiC/SiC 1	3	3	9
SiC/SiC 2	3	3	9
SiC/SiC 3	3	3	9
Total			84

Assuming that the three dose levels in column 3 of table 4 are 50 dpa, 100 dpa and 150 dpa, requiring irradiation times of 3.6, 7.1 and 10.7 years respectively, and that the high flux module is always loaded with samples representing 13 material conditions (i.e. all non-structural materials excluded), this programme would have required 46 years for its completion!

3.3 Fast Track Recommendations

It is evident from the preceding section that the irradiation programme has to be optimised substantially for the fast track programme. The vital conclusion of the fast track programme is the construction and operation of DEMO. A large majority (but not unanimous) opinion within the materials community is that neither vanadium alloys nor SiC/SiC composites are likely to be used as the main structural material at that stage of fusion development. Therefore a first decision is to prioritise the IFMIF programme for work on steels, deferring all work on advanced materials. This alone reduces the DEMO-relevant length of phase 2 from 46 to 16 years.

Within the restriction to a ‘steels-only’ programme, two levels of risk are available. By retaining the 16 year programme, RAFM and ODS steels could be tested in parallel leading to a choice of material. At higher risk, all initial efforts could be concentrated on either RAFM (currently the best-developed option) or ODS (more promising with respect to limitation of helium-induced swelling) leading to a 10 year programme.

The overall schedule from project start to the availability of DEMO design data is summarised in the final two columns of table 5. The following assumptions have been applied:

1. The IFMIF ‘CODA’ phase follows immediately from the end of the ‘EVEDA’ phase. This requires either (and preferably) that the two are merged and commence with a siting decision, or that the siting decision and concomitant negotiations are conducted within the EVEDA time frame;
2. The EVEDA phase is reduced from five to three years and both accelerators would be constructed and commissioned within a seven-year CODA. This presumes a higher rate of expenditure than the CDR assumption, but leads to an overall design and construction time of ten years;
3. The phase 1 (single accelerator) operational programme (insofar as this is needed at all) would be completed within the ten-year EVEDA+CODA time frame;
4. Three years is needed for post irradiation analysis of the last batch of samples and incorporation of the materials data into a pre-existing DEMO design.

The assumptions 1-3 above are in agreement with the conclusions of a recent EFDA study [A5], which gives ten years for the R&D, design and construction of IFMIF, up to full phase 2 operation (including 1.5 years of single accelerator operation).

Table 5. IFMIF Fast Track Schedule Options (Years)

	CDR schedule (1)		**Fast Track schedule (2)**	
	RAFM & ODS testing	**RAFM or ODS testing**	**RAFM & ODS testing**	**RAFM or ODS testing**
EVEDA + CODA	12	12	10	10
Phase 1 operation	3	3	0	0
Phase 2 operation	16	10	16	10
Post irradiation analysis and DEMO design changes	3	3	3	3
Total	34	28	29	23

(1) The initial 12-year period ends with the commissioning of the first accelerator, and so is followed by the 3-year phase 1 operating period.

(2) Phase 1 operation is assumed to be completed in years 9 & 10 of construction [A5].

4. Conclusions

The main conclusion emerging from this annex is that, **on the most prioritised schedule considered, the necessary materials and technology information from the ITER TBM and IFMIF programmes could be available in year 23. As discussed in section 7 of the main body of this report, much of the information – that required for Phase 1 of DEMO - could be available much earlier.**

The principal assumptions underlying this conclusion are:

IFMIF:

- EVEDA + CODA completed in ten years;
- Phase 1 (if needed) completed in the EVEDA + CODA phase;
- International agreement is reached on (a) the choice of the main DEMO structural steel, and (b) on the absolute priority use of phase 2 for this material until it is qualified for DEMO.

ITER TBMs:

- Only one structural material will be qualified by IFMIF on the DEMO time scale, so the TBMs using this material, and other near-term choices, should be given priority if any programmatic conflicts arise.

References

[A1] ITER Final Design Report: Design Description Document 5.6: Test Blankets (July 2001).

[A2] IFMIF Conceptual Design Activity (CDA) report, ENEA Frascati Report RT/ERG/FUS/96/17 (1996).

[A3] IFMIF Key Element Technology Phase (KEP) report, JAERI-Tech 2003-005, March 2003 (Pp. 428 – 432).

[A4] IFMIF Comprehensive Design Report (CDR), IEA (January 2004).

[A5] EFDA-STAC 10/4.2 (September 2004), "Status of the IFMIF assessment by EFDA: IFMIF construction time schedule".