The Role of DEMO in a Fast-Track Development of Fusion Power

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ABSTRACT. This paper is concerned with key aspects of issues for DEMO, emerging from European studies of commercial fusion power plant conceptual designs and of accelerated development of the first generation of commercial fusion power plants. The urgent need to find global solutions to the provision of environmentally benign sources of power has led to widespread acceptance of a 'fast track' approach to fusion development. Fast track studies have analysed *inter alia* the requirements on DEMO(s) that would form the only step between the ITER/IFMIF generation of devices and the first generation of commercial plants. Fusion power plant studies have shown that power plants with very attractive safety and environmental features and viable economics may be achieved on the basis of relatively near-term plasma physics together with components focussed on reduced activation martensitic/ferritic steels as the structural material. Using further technical work developing the above studies, the plasma physics, technology and materials selection issues for DEMO are analysed.

1. Introduction

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. The urgent need to find global solutions to the provision of environmentally benign sources of power has led to widespread acceptance of an accelerated (fast track) approach to fusion development [1,2,3].

Fast track studies [4,5] have analysed *inter alia* the requirements on electricity-generating prototype power plants (DEMOs), which would form the only step between the ITER/IFMIF generation of devices and the first generation of commercial plants. This paper is concerned with key aspects of the plasma physics, technology and materials selection issues and requirements for DEMO, as these have emerged from the combination of recent European studies of: (i) commercial fusion power plant conceptual designs - the Power Plant Conceptual Study (PPCS) [6,7,8] and its follow-up; (ii) fast track development of the first generation of fusion power plants (especially the conclusions of the recent UK study [5]). Fusion power plant studies [6,7,8] have shown that the creation of power plants with very attractive safety and environmental features and viable economics may be achieved in conceptual designs based on relatively near-term plasma physics together with components focussed on reduced activation martensitic/ferritic steels as the structural material.

Using further technical work developing the above studies, this paper analyses the plasma physics, technology and materials selection issues for DEMO, and the prioritisation of R&D. Section 2 contains a summary of the pertinent results from the PPCS [6,7,8] (Plant Models A, B, C and D), plus the additional Model AB that has been analysed in follow-up work. The elements of a further Model, C*, are introduced. In section 3, an assessment is made of the potential of these Models as first generation commercial power stations and the elements of a further Model, B*, are introduced. The crucial points from the recent Fast Track study [5] are given in section 4, focussing on the role of, and requirements for, DEMO. Section 5 develops further the points emerging from sections 3 and 4 in relation to choices for DEMO, and section 4 draws some conclusions on the prioritisation of R&D.

2. Fusion Power Plant Studies

The European Power Plant Conceptual Study (PPCS) developed and analysed four conceptual designs, termed "Models", of commercial fusion power plants. These span a range from relatively near term, based on limited plasma physics and technology extrapolations, to an advanced conception. The technical bases of the four Models, A – D, and the results of the analyses, are briefly summarised below, giving only the key points pertinent to this paper. Full details are given in the PPCS Report [6] and summaries of the key features and results, more extensive than can be given here, are also available [7,8].

For the two near-term models, A and B, the plasma physics scenario represents broadly parameters about thirty percent better than the conservative design basis of ITER. Models C and D are based on progressive improvements in the level of assumed development in plasma physics, especially in relation to plasma shaping and stability, limiting density and in minimisation of divertor loads without penalising the core plasma conditions.

Model A is based on a liquid lithium-lead blanket with water cooling. The structural material is the reduced-activation ferritic-martensitic (RAFM) steel Eurofer. The divertor – an extrapolation of the ITER divertor design - is water-cooled copper alloy with tungsten plasma-facing armour, with a tolerable heat flux of 15 MW/m^2. The Model B blanket is based on lithium orthosilicate and beryllium pebbles, cooled by helium, with Eurofer structure. Helium coolant is also assumed for the divertor, with tungsten alloy and Eurofer structural material. Innovative designs of divertor, based on the coolant jet impingement principle and flow in very narrow channels, were considered, permitting a tolerable heat flux of 10 MW/m^2. Model C has a lithium-lead blanket in which heat is removed by circulation of the lithium-lead itself and helium. The structure is oxide-dispersion-strengthened RAFM and Eurofer. The lithium-lead flow channels are lined by silicon carbide composite inserts, providing thermal and electrical insulation, but having no structural function. The divertor is the same as for Model B. The technology of Model D is advanced, using silicon carbide composite as a structural material. Table 1 further summarises the physics and materials bases of the Models.

TABLE 1. SUMMARISED PLASMA PHYSICS AND MATERIALS BASES OF THE PPCS MODELS

PPCS Model	Plasma physics	Main structural material	Other blanket materials	Other divertor materials
A	Near-term	Eurofer	LiPb/water	W/Cu/water
B	Near-term	Eurofer	Li4SiO4/Be/helium	W/helium
C	Intermediate	Eurofer/ODS	LiPb/SiC/helium	W/helium
D	Advanced	SiC/SiC	LiPb	W/SiC/LiPb

Extensive analyses were performed of the safety, environmental impacts and economics of the PPCS Models [6,7,8]. Only the main relevant results are summarised here.

The economics of fusion power improves substantially with increase in the net electrical output of the plant: essentially because the fusion power increases more rapidly than the plasma current drive power requirement. For this reason, the target net electrical output of the PPCS Models was chosen to be 1,500 MWe. For given net electrical power output, the required fusion power is determined by the thermodynamic efficiency and power amplification of the blankets and the amount of gross electrical power recirculated for purposes including plasma current drive and coolant pumping. The result of these factors is a fall in the fusion power from Model A to Model D. Given the fusion power, the plasma size is determined by the assigned constraints on plasma physics relating to restricting the heat loads to the divertor, and by the tolerable heat flux to the divertor. Taken together, these factors lead to a fall in the size of the plasma, from Model A to Model D, as shown in Fig. 1.

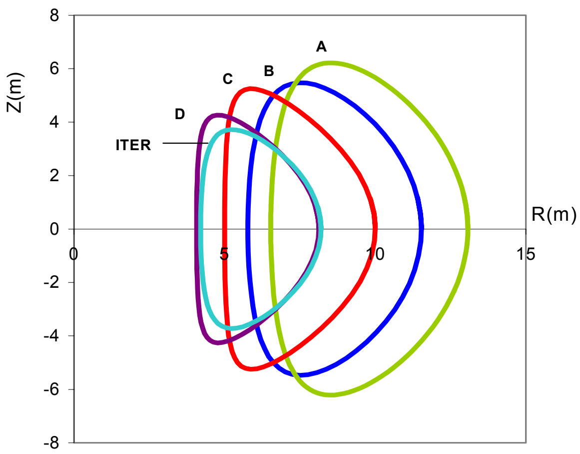

Fig. 1. The sizes and shapes of the plasmas in the four PPCS Models. For comparison, ITER is also shown: this is similar in size to Model D. The axes labels denote major radius (R) and height (Z).

The above variations in size, together with the lower recirculating power of the smaller Models, lead to a fall in the cost of electricity from Model D to Model A. The calculated ranges of cost of electricity are shown in the first four rows of Table 2. The cost range given for Model B is slightly higher than appeared in the PPCS Report [6] as a result of taking into account the reduction in net electrical power arising from re-estimation of helium pumping power [9]. However, it is clear that a re-optimisation of the design parameters would result in a fall in these costs to an intermediate value.

TABLE 2. CALCULATED INTERNAL COST OF ELECTRICITY FROM THE MODELS

Model	**Cost of electricity (Eurocents/kWh)**
A	5 – 9
B	5 – 9
C	4 – 7
D	3 - 5
AB	5 - 9
C*	4.5 – 8.5

These calculated costs are in the range of published estimates for the future costs of electricity from other sources [9,10]. Economic optimisation of the designs did not jeopardise their excellent safety and environmental attributes: these derive from inherent features of fusion, together with materials selection. All the Models proved to have the attractive and substantial safety and environmental advantages of fusion, established with great confidence [6,7,8].

After the conclusion of the PPCS, a follow-up study was launched that considered a new Model, termed Model AB. Model AB is based on a lithium-lead blanket, but cooled by helium rather than water, with the helium-cooled divertor of Model B. Model AB has the same plasma physics basis as Models A and B. The conceptual design has been developed and analysed [11,12] in the same manner as was done for the PPCS Models.

In comparing Models A and AB, a significant issue is the higher levels of power needed to pump the helium coolant in Model AB. The outcome of the systems analysis is that the size of, and economic performance of, Model AB are close to those of Model A. Compared to Model A, the benefits of higher blanket operating temperature in Model AB (arising from the helium cooling) are approximately counterbalanced by the disbenefits of the higher pumping power and lower divertor heat load. The calculated range of cost of electricity is shown in Table 2 [11]. Further optimisation of the conceptual design may reduce the pumping power and improve the economics. Safety and environmental attributes of Model AB are similar to those of the other Models [12,13].

Although the plasma physics basis of PPCS Model C is intermediate, its technology is relatively near-term, since the silicon carbide composite is not employed in any structural capacity. It is readily possible to construct the elements of a further near-term Model, Model C*, with the blanket and divertor of Model C but the plasma physics of Models A, AB and B. The safety and environmental attributes of Model C* are confidently expected to be similar to those of the other Models. Systems analysis shows that the economics of Model C* is similar to that of Model B [14]. The blanket temperature (and so the thermodynamic efficiency) of Model C* are higher, and the helium pumping power is lower, than those of Model B. However these favourable economic factors are counterbalanced by Model C*'s lower blanket power amplification (owing to the absence of beryllium) and the greater thickness of its neutron shield. The range of calculated cost of electricity is shown in Table 2.

3. Assessment of the Models

It is clear that Model D, with both advanced plasma physics and advanced technology, is not a candidate for the first generation of commercial power plants. Accordingly, Model D will not be considered further in this paper. Model C, with intermediate plasma physics and near-term technology, presents a less clear case. However, in the context of a fast track route to DEMO, it seems reasonable to disregard Model C also, at least for the purposes of this paper. It remains to consider Models A, AB, B and C*.

All these Models differ little in their economic attributes, with Model A being, marginally, the least attractive in this respect.

All the Models display in large measure the safety and environmental advantages of fusion. However, they are not totally equivalent in this regard. The good safety characteristics of Model B are contingent upon design measures to preclude the dissociation of zirconium hydride in the neutron shield, with resulting hydrogen production, in hypothetical bounding accident scenarios. There is no doubt that this can be done, but it was only marginally achieved for the specific design parameters of Model B. Reverting to earlier design concepts, with a water-containing shield, would be unsatisfactory, since the remote possibility of beryllium-water chemical reactions producing hydrogen in hypothetical bounding scenarios would be incompatible with a totally inherent/passive approach to fusion safety. An approach that resolves this issue very decisively is to use a tungsten carbide shield. The neutronics, activation and waste management characteristics of this approach have been studied [15]. The outcome is entirely satisfactory except that a small increase in the inboard shield thickness may be required, which would entail a small economic penalty.

Accordingly, it is appropriate to introduce the elements of a further near-term Model, termed Model B*, that is similar to Model B but with a shield based on tungsten carbide. Model B* may have marginally worse economics than Model B.

Models A, AB, B* and C* are all good candidates for attractive first generation fusion power plants. It remains to consider these Models as DEMO candidates, in the context of a fast track development of fusion.

4. Fast Track Studies

This section gives a brief summary of the recent UK Fast Track study [5], focussed only on the key points for the role of DEMO. Full details can be found in the Report [5]. In broad outline and overall timescales, and in many of the details, this study agrees with an earlier European study [4] and with Japanese Fast Track proposals [2]. The study adopts as the target for the outcome of the fusion development process a first generation of commercial fusion power plants similar to any of the Models A, AB, B* or C* discussed above.

The approach taken to the appropriate timescale of fusion development, and to risk, was motivated by an analysis [16] of the way that the economic value of fusion development depends on key aspects of the planned path. This work divided fusion development into its key stages, ascribed costs, time-scales and success probabilities to these stages and used a sequence of decision points to map a route to the end point of the development programme. Depending on aspects such as technical success, cost, and developments in the external energy market, the end point varies between a large contribution (20%) of fusion to the electricity market by the end of the century and a curtailment of the fusion programme because the new energy source is not required or not economically viable. An important part of the study was to look at how the time-scale to fusion power can be reduced, the possible effect of such a reduction on success probabilities at each stage and how these can be managed, and consequently the effect on the economic value of fusion development. It was found that, because discounting lowers the present value of future benefits, developing fusion more quickly increases the economic (net present) value, notwithstanding that the development risks and short-term costs are increased. This is illustrated in Fig. 2.

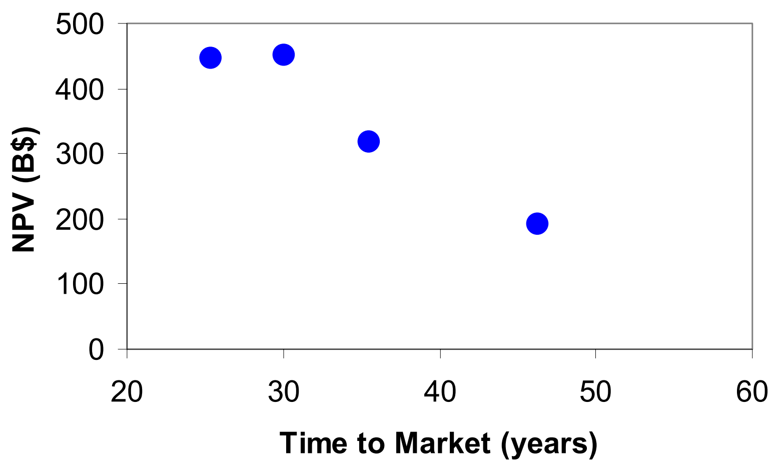

Figure 2. Reducing the development time for fusion, by parallel and accelerated operation of facilities, increases the Net Present Value of developing fusion, even after accounting for increased short-term development costs.

When considered alongside the present environmental imperative to modify our energy systems, this potential for increased value argues very strongly for a faster development of fusion power. Accordingly the Fast Track [5] study envisages two stages to the development process: the ITER/IFMIF stage and the DEMO stage, leading directly to the first generation of commercial plants.

In the second stage of the fast track, the device(s) 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, 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.

The requirements for DEMOs derive from their roles in bridging the gap between the ITER/IFMIF generation of devices and the commercial power plants. A DEMO must:

- Be based on the plasma physics basis developed by ITER, and must confirm this in higher fusion power, commercial size, devices similar to Models A, AB, B* and C*.
- 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 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.

The technical considerations were analysed and developed into a reference fast track, shown in Fig. 3, and a variant fast track in which the deployment of ancillary devices achieved some further acceleration and risk reduction [5]. Means for further acceleration and expansion of options were discussed, for instance by having several IFMIFs and several DEMOs in parallel. For the purposes of this paper, only the fast track shown in Fig. 3 will be discussed. In brief summary, the main measures needed to achieve the timescale of Fig. 3 are as follows.

1. ITER plasma physics and plasma engineering activities must be firmly focussed on providing as early as possible the crucial confirmation of reliable 'good enough' plasma regimes for DEMO based on near-term plasma physics, rather than going for 'peak performance'.
2. The investigation of issues relating to plasma-materials interactions, especially divertor issues, should receive priority on ITER.
3. The ITER Test Blanket Modules, and their testing plan, must be exclusively focussed on the near-term blanket candidates (Models A, AB, B* and C*) for DEMO Phase 1.
4. As indicated in a recent EFDA paper [17], the design and construction of IFMIF should be sharply accelerated compared to earlier severely resource-constrained plans.
5. The IFMIF testing plan must initially be firmly focussed on the near-term structural material candidates for DEMO, based on Models A, AB, B* and C*.
6. The permanent components of DEMO will only experience low levels of (substantially low energy) neutron fluence. Materials for these roles therefore only need relatively low levels of exposure in IFMIF.
7. Since the first Phase of DEMO will have low availability, the first set of DEMO blankets and divertors will only experience neutron fluences of order 3-4 MWy/m^2. The corresponding materials therefore only need exposure to these limited levels, corresponding to about 40 dpa, in IFMIF in order to validate Phase 1 design.
8. Being based on some conservatism, DEMO can be licensed on the basis of the information provided by ITER and IFMIF together with the use of validated modelling to extrapolate from ITER and IFMIF results. Thus a model validation programme should be given priority, especially in the relatively underdeveloped materials area.
9. Existing and projected stocks of tritium, after allowing for natural decay, will be sufficient for the operation of ITER and, with a small margin, DEMO. However, there is some risk of shortfall 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 dedicated research-reactor-size fission plants, but this is an expense that should be avoided – by proceeding rapidly with the fusion development programme.

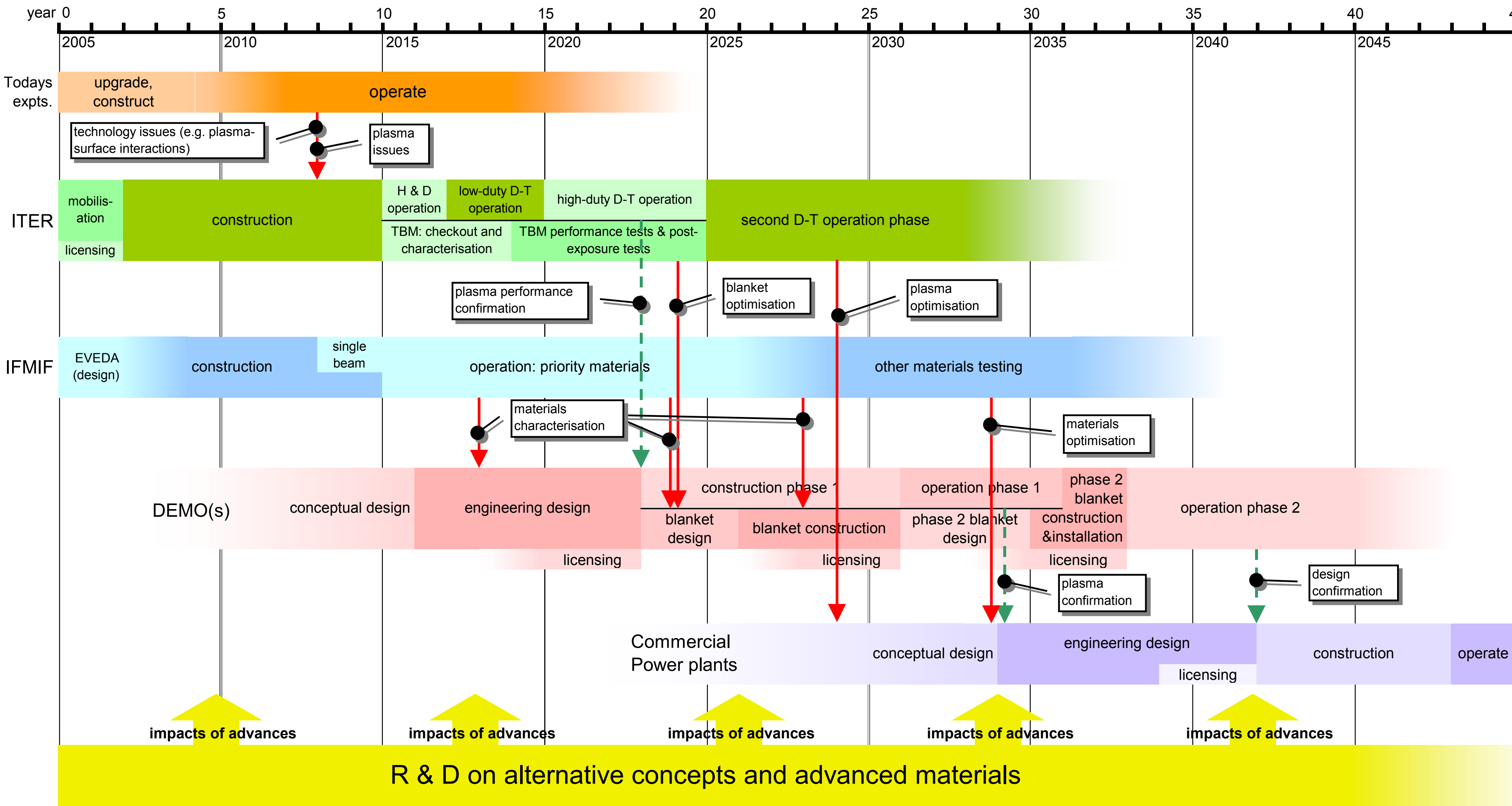

Figure 2. Possible sequence of existing and main future devices in the reference Fast Track programme.

5. Development of Issues for the Role of DEMO.

In a fast track programme for fusion, the time for hard choices is rapidly approaching. The main issues are discussed in this section, in the light of the above results and considerations.

First: plasma physics. Assuming ITER's success in developing the basis and understanding of good candidate plasma regimes, there remains a gap between ITER and a commercial power plant because of the necessarily larger physical dimensions of the latter. As explained earlier, the different scalings of fusion power and current drive power with size require, for the non-advanced plasma regimes of Models A, AB, B* and C*, that a commercial plant is larger than ITER. If DEMO were to have the dimensions of the commercial plants, there need be no extrapolation from DEMO to commercial, but there would be an extrapolation from ITER to DEMO. Furthermore, a first-of-kind DEMO that was the size of a commercial plant and was conservatively designed as suggested above, would have a high capital cost. These tradeoffs would be considerably eased if the net electrical output of the commercial plants was reduced to 1,000 MWe, with a corresponding reduction in the physical dimensions of these plants, and so of DEMO. However, this would increase the cost of electricity by almost twenty percent.

Secondly: materials and technology. Models A, AB, B* and C* are very similar in their safety, environmental and economic attributes. The water-cooled Model A has a simple divertor design that is an extrapolation of the divertors that will be tested in ITER, and its balance-of-plant is based on existing well-qualified technology. For these reasons it seems to be the leading candidate for the DEMO concept, if there is only one DEMO. The helium, or part-helium, cooled Models AB, B* and C* rely on a divertor concept that might only be tested in ITER in the form of Test Divertor Modules at a relatively late stage. These divertor designs have helium flow in very narrow channels, which could be vulnerable to irradiation-induced swelling and creep in DEMO neutron fluences, imposing more stringent demands on materials testing and model validation. These problems could be alleviated by reducing the target heat flux, or removed by accepting a water-cooled divertor (though this second solution would not be acceptable for Model B*, and would entail three coolants for Model C*): in each case there would be a small economic penalty.

Assuming the success of ITER, the ITER Test Blanket Modules (TBMs) and IFMIF, it seems likely that they would be followed by several DEMOs. The operation of several DEMOs, for example using different blanket and divertor conceptions and/or plasma operation scenarios, would greatly relax the above problems: widening, and promoting the optimising of, choices for the design of the first commercial plant, without delaying the programme.

4. Resulting Priorities for R&D

Success requires a firm top-down organisation of the ITER, ITER TBM and IFMIF programmes, to enforce the priorities listed in section 4, and others given in the Report [5].

It is clear also that there must be a water-cooled lithium-lead (WCLL) Test Blanket Module to test Model A issues, and indeed that this should be the centrepiece of the ITER TBM programme. Helium-cooled or dual-cooled TBMs, along the lines of Models AB, B* and C*, are clearly required. Given that there are only three ITER ports available for the TBMs, each capable of accommodating two TBMs, it is likely that there should be no 'advanced' TBMs.

An optimised structural material for helium-cooled divertors needs to be developed, and thought given urgently to how helium-cooled divertor concepts could be studied on ITER.

5. Concluding Remarks

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.

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