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Evolving targets for DEMO: Implications for materials development

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ABSTRACT

Current reference fusion development scenarios assume the sequential achievement of key milestones. Firstly, the qualification of the plasma physics basis in ITER, together with the qualification of materials for in-vessel components in IFMIF. Secondly, the qualification of components and processes in DEMO. However, the circumstances, within which fusion development planning is undertaken, are changing, and it is becoming reasonable to plan on the assumption that within 20 years ITER and IFMIF will have been successful and the world will be eager for clean, secure energy supplies. This motivates supplementing the reference scenario with the consideration of reduced targets for the economic performance of a first generation of fusion power plants that could be deployed as early as possible, and so reduced targets for the technical performance of early DEMOs. The implications of the reference scenario and variants for fusion materials development are considerable, and these are discussed in this paper.

1. Introduction and background

Current reference fusion development scenarios assume the *sequential* achievement of key milestones. Firstly, the qualification of the DEMO/power plant plasma physics basis in ITER, together with the qualification of materials for in-vessel components in IFMIF. Secondly, the qualification of components and processes in DEMO. Although these scenarios are constrained by budgetary considerations, they require the resolution of many issues in physics, technology and engineering.

However, the context of fusion development planning is changing. Confidence in fusion has greatly increased: the ITER Treaty and the Broader Approach Agreement have removed much uncertainty relating to the near-term steps of fusion development. Authoritative publications by the Stern Review [1] (by the former Vice-President and Chief Economist of the World Bank) and the Intergovernmental Panel on Climate Change [2] have removed most of the uncertainties about the cost, reality, causation and pace of climate change. Government decisions and public support have displayed increasing commitment to mitigating climate-changing emissions. It is becoming widely appreciated that during the second two-thirds of this century continued world economic development, and continued growth in energy consumption, must co-exist with the reduction of carbon emissions to very low levels, and that this will give rise to large political and economic forces. Concerns over energy security and diversity of supply have also markedly increased.

Thus, it has become reasonable to plan on the assumption that within 20 years ITER and IFMIF will have been successful and the world will be eager for clean, secure energy supplies. This motivates supplementing the fusion development reference scenario with the consideration of reduced targets for the economic performance of a first generation of fusion power plants (FPPs) that could be deployed as early as possible, and so reduced targets for the technical performance of early DEMOs. These ideas are beginning to be analysed seriously in Europe.

The implications of the reference scenario, and variants, for fusion materials development are considerable, and these are expanded on in this paper. Section 2 outlines the essence of reference, 'sequential, restricted-funding', fast track development scenarios [3–6] and their expected economic outcomes. Section 3 discusses implications of climate change mitigation and energy security. The threads are drawn together in Section 4, and used to motivate ideas for more rapid evolution of fusion power with less ambitious technical targets for DEMO and the first generation of power plants. Section 5 discusses the implications for fusion materials research and development. Conclusions are summarised in Section 6.

It must be stressed that all the development plans discussed, including the considerations advanced in this paper, fully preserve the major safety and environmental advantages of fusion power [7–10], which are key to securing social acceptance for it's widespread deployment.

2. Reference 'fast track' fusion development scenarios

The essence of conventional – 'funding-constrained, sequential' – scenarios for the development of fusion [3–6,11,12], is that: development and qualification of materials occurs on the same

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timescale as ITER; there is a single stage, DEMO(s), between the ITER/IFMIF stage and the launching of the first generation of power plants. A key additional assumption is that DEMO construction starts only after the establishment of the DEMO plasma physics basis in ITER. An almost inevitable consequence of the sequential assumption, and of the time needed to construct, license and exploit large devices, is that demonstration of electricity production by fusion does not occur until up to about 30 years. A conspectus of fusion development scenarios of this type is shown as the 'Reference Programme' in Fig. 1: from Ref. [13], which contains valuable discussion. Other scenarios [3–6,11,12] differ in detail but are broadly similar.

Discussion of the issues to be addressed in the main, and supplementary devices, was given in Ref. [6]: an updated and extended summary is presented here as Fig. 2 [14]. A more extended presentation (differing in the details of its formulation) of required qualification, validation and demonstration tasks was given in Ref. [11].

All these plans assumed – explicitly or tacitly – continuation of funding at about the present level. This level is low: the whole cost of developing fusion to fruition is equal to only a few days of world consumer spending on energy; the cost of constructing ITER is about the same as the cost of constructing a small west European town (10 000 households). There is a similar adverse picture for energy R&D as a whole: total world public sector energy R&D is about ten billion dollars annually, equal to about a day of consumer spending on energy – not much to solve a major global problem!

What are the likely economic characteristics of fusion power plants developed by programmes along the lines outlined above? A number of detailed studies have been made – see, for example, [7–10,15–18] – that are broadly in agreement. The estimated range of costs of electricity from near-term fusion power plant designs is comparable with the estimated ranges of projected internal costs of electricity from other environmentally responsible energy sources. There are, of course, significant uncertainties associated with all such projections.

Thus these 'fast track' fusion development scenarios, with pace and risk aversion dictated by severe funding constraints, result in a very good outcome – very safe and environmentally benign power plants with competitive internal costs of electricity. Until fairly recently, this would have been regarded as an entirely appropriate and defensible position. However, as emphasised in the Section 1, everything is changing! Does this mode of developing fusion power deliver its ***widespread*** deployment early enough to make an economically optimal contribution to mitigation of global climate change?

3. Climate change, energy security, and their implications

Calculations of the environmental impacts of different global climate change scenarios, of the climatic consequences of various scenarios for greenhouse gas emissions, and of the emissions arising from different scenarios for world and regional economic development, are all subject to significant uncertainties. However, the broad conclusions are clear [1,2,19]. The modeling strongly indicates that: whilst a temperature rise of 2 °C might be acceptable, though not certainly desirable, it would be dangerous to allow a rise of 3 °C or more; to have a good chance of staying below a rise of 3 °C, greenhouse gas concentrations need to be kept below about 500 ppm CO_2e. Typical emission scenarios, based on economic modeling, which stabilise atmospheric concentrations at this, or lower, levels illustrate well a point made forcefully by the authors of the recent comprehensive report 'Avoiding Dangerous Climate Change' [19]:

> 'In the first approximation, concentrations and temperature changes are a function of cumulative emissions. This implies that future global emissions trajectories have to curve through a maximum some time this century (during the next decade or two for stabilisation at relatively low levels of, say, 400–500 ppmv and a few decades later for high levels), and proceed to decline well below current levels towards the end of the

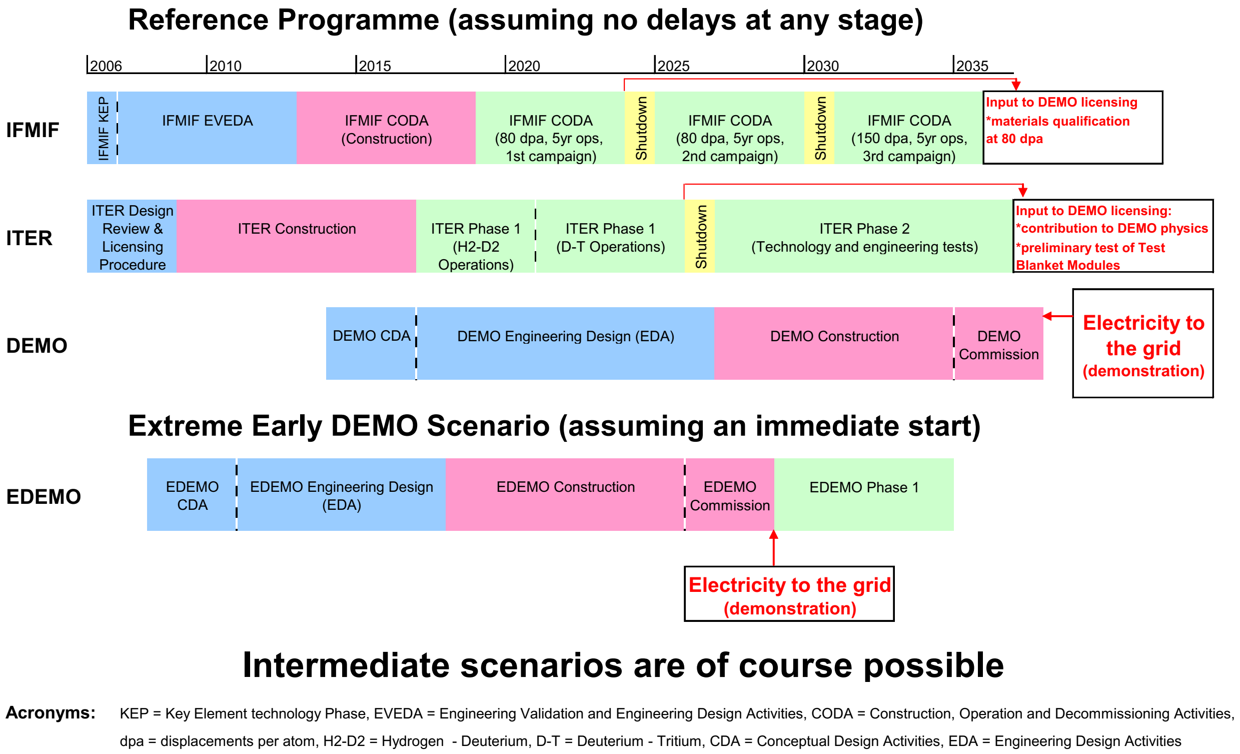
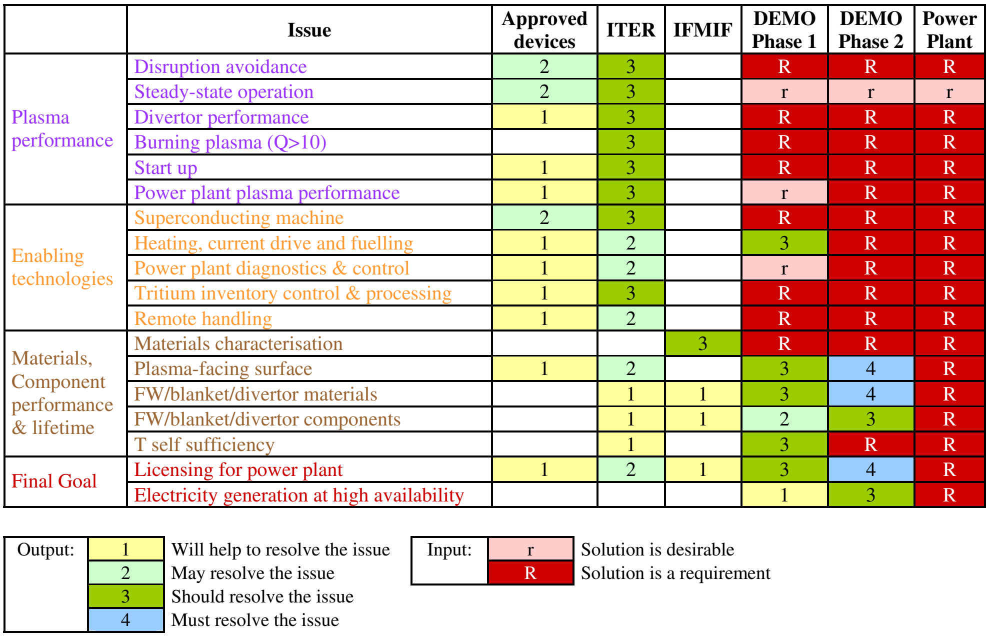


Fig. 1. Conspectus of reference and accelerated scenarios for the development of fusion power (from Ref. [13]).



	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady-state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Heating, current drive and fuelling	1	2		3	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Remote handling	1	2		R	R	R
Materials, Component performance & lifetime	Materials characterisation			3	R	R	R
	Plasma-facing surface	1	2		3	4	R
	FW/blanket/divertor materials		1	1	3	4	R
	FW/blanket/divertor components		1	1	2	3	R
	T self sufficiency		1		3	R	R
Final Goal	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

Output:	1	Will help to resolve the issue
	2	May resolve the issue
	3	Should resolve the issue
	4	Must resolve the issue

Input:	r	Solution is desirable
	R	Solution is a requirement

Fig. 2. Summary of issues to be addressed in the development of fusion power (adapted and updated from an earlier version in Ref. [6]).

> century. This is a tall order from the current perspective……. What is more controversial, however, is whether now-known technologies can achieve this momentous global undertaking or whether fundamentally new options, such as fusion, that are still technically not feasible, might be required.'

During the second two-thirds of the century, the continuation of economic development in currently less-developed countries, co-existent with the reduction in emissions to low levels, will generate large political and economic forces and opportunities. In particular, it appears that the opportunities for fusion to contribute cost-effectively to climate change mitigation may be greatest if it can be deployed early enough, even in a non-ideal form, and that higher rates of fusion development expenditure would be amply justified from an economic perspective. These intuitions are supported by the pertinent economic analyses that have been performed. The Stern Review [1] found that the costs of climate change are far higher than the costs of measures that would mitigate it, and that economics mandates that investment in energy research and development should at least double, specifically citing fusion as one of the four priorities for scientific progress. (One of the other three priorities was stated to be 'materials', so fusion materials R&D qualifies twice!).

These conclusions were prefigured, and the role of fusion considered in detail, in seminal economic research, funded by the European fusion programme but performed by independent experts, a decade ago [15,16,20] . This work used a well-established detailed model (MARKAL) to simulate the evolution of the West European economy to the end of this century, determining the cheapest (discounted) way to supply the demand for energy subject to constraints such as a cap on atmospheric CO_2 – see [15,16,20] for further detail and discussion. In these models, fusion captured about 20% of the West European electricity market in emission-constrained scenarios. A detailed examination of the results shows that fusion could not capture a larger share of the market because, on the assumptions made at that time (1997), it could not be deployed fast enough. Broadly similar conclusions were reached in a Japanese study using a world model [21]. In all these cases, the sums involved are huge, dwarfing the costs of fusion development, amply justifying fusion development from the economic viewpoint and strongly suggesting that it would be more optimal economically to spend more on fusion development to produce fusion power earlier. Studies of the economic value of developing fusion at different speeds, taking into account the varying costs and resulting changes in the probabilities of failure, have been performed [18,22]. The economic value of developing fusion was substantially positive in all but the most pessimistic scenarios, and was highest for early deployment.

Regarding energy security, fusion has very abundant, accessible and widespread economically viable fuel resources (lithium, and deuterium from sea water): by far the largest of any energy source [18]. Thus it potentially can make a major contribution to the resolution of future energy security issues, as well as to global climate change mitigation. Energy security imperatives may inhibit the most cost-effective fully-globalised deployment of some climate-change-mitigating energy sources, but this would not be a factor for the deployment of fusion.

4. Accelerated development of fusion

The considerations discussed in the previous sections suggest that: higher levels of fusion development funding are economically justified, and could be used to break the 'sequential' assumption in fusion development planning; an earlier first generation of fusion power stations would be economically justified, even with reduced cost performance, and this may be the economically optimal scenario.

Conventional ways to accelerate, and reduce the risks of, fusion development were discussed in Ref. [6], for example by the deployment of ancillary devices. However, as emphasised elsewhere [11], a more decisive acceleration entails breaking the 'sequential' assumption. Consideration should be given to an early DEMO (EDEMO), beginning construction in about 10 years and demonstrating electricity production in about 20 years – see, for example, the lower diagram in Fig. 2 and Ref. [13] for valuable discussion. Results from ITER and from the first campaign at IFMIF would still be available in time to underwrite a request for a license to operate EDEMO. There would be time also for ITER to develop two or three 'good enough' plasma operational scenarios, for quick optimization in EDEMO. The major advantages of 'learning by doing', accelerated involvement of industry, and earlier engagement with issues such as component reliability development and long-term exposure of surface materials to co-existent heat and neutron fluxes, can be weighed against the risk of failing to fully achieve the objectives or incurring abortive expenditure. These risks and possible costs are very small compared to the risks and costs associated with global climate change. Necessarily, the technical objectives for EDEMO would be relaxed, such as: plasma performance similar to ITER, and moderate power density; long-pulse operation, if steady-state is not available in time; a near-term, less efficient, blanket concept; a reduced lifetime-fluence target for the blanket structural steel.

A preliminary technical discussion of DEMO, and associated power plant, options was given in Ref. [23]. In particular, long-pulse (about 10 h) fusion power output, with energy storage to produce steady net electric power, might incur an economic penalty of about 20% – this is difficult to estimate at this stage, being the balance between factors such as energy storage and measures taken to reduce the effects of fatigue, which increase costs, and offsetting factors such as reduced re-circulating power and capital equipment associated with current drive and reduced requirements on plasma-facing components. For fixed net electric output, the size of a pulsed device is automatically larger [23] than a steady-state device, producing the following beneficial consequences, from the viewpoint of early development: easier maintenance; reduced load on the divertor; reduced neutron flux to the first wall; reduced power needed for heating and current drive. The economic considerations summarised in this paper suggest that an early generation of power plants, based directly on the above, or similar, EDEMO conceptions would be likely to be economically acceptable, but this requires more detailed study.

5. Implications for fusion materials

In this section, a preliminary discussion is given of the main implications, of both reference and further-accelerated scenarios, for fusion materials, and materials-related, research and development.

In either the reference or further-accelerated scenario, the disciplined approach of an industrial R&D programme is essential. ITER and IFMIF must not be treated as user-facilities: on the contrary, they must have top-down-coherent, firmly-directed, programmes giving absolute priority to rapid provision of information on near-term options for materials and blankets. ITER must operate with tungsten-based plasma-facing surfaces as early as possible, as these are the only known near-term possibilities for DEMO/EDEMO conditions. Regarding the ITER Test Blanket Modules (TBMs): though there are half-ports available for only six TBMS, the ITER parties currently have proposals for over 10. There is much overlap of concepts, some advanced and possibly infeasible concepts, and the significant omission of what is possibly the most conservative concept – the water-cooled lithium–lead. An agreed TBM programme needs to be constructed that is coherent as a whole, exploring only the key issues for near-term conservative blankets, with the main focus on the least aggressive of these, until much later in the ITER programme. The selection of materials for testing, and re-testing, in IFMIF also needs to be disciplined, focusing only on the near-term structural and plasma-facing materials, such as Eurofer and similar, and tungsten-based alloys. Time and space will not be available for advanced materials, until much later in the IFMIF programme. The initial test fluences for materials for in-vessel components can be limited to the fluence that the target component will experience in the first (low availability, hence low fluence) phase of DEMO. All possible measures should be taken to promote the optimal selection of materials for testing in IFMIF and for the TBMs, including the development of physical understanding and predictive modeling capabilities validated by proxy irradiations (such as multi-ion-beams), and by the exploitation of fusion–fission materials synergies.

In the further-accelerated scenario, materials R&D would need to concentrate on the nearest-term choices of materials for the nearest-term conservative option for the EDEMO blanket. The consideration of fatigue, and creep-fatigue interactions, would have higher profile. Materials R&D for energy storage could become a significant part of the fusion materials programme, as part of wider programmes to address such issues.

6. Summary of conclusions

The new context of fusion development planning justifies serious consideration of a radical change to the basis of fusion planning scenarios, involving *inter alia*: a relaxed target for the internal cost of electricity from the first generation of fusion power plants; correspondingly reduced targets for the technical performance (e.g. pulsed plasma scenarios, lower materials endurance, lower blanket efficiency) of DEMO(s); demonstration of fusion electricity production in 20 years, leading to widespread deployment of fusion power earlier than in previous fast track scenarios. The implications for fusion materials R&D include the need to accept the disciplined approach of an industrial R&D programme giving absolute priority to the rapid provision of information on near-term options for materials and blankets.

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