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The value of materials R&D in the fast track development of fusion power

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Abstract

The objective of the international fusion program is the creation of power plants with attractive safety and environmental features and viable economics. There is a range of possible plants that can meet these objectives, as studied for instance in the recent EU studies of power plant concepts. All of the concepts satisfy safety and environmental objectives but the economic performance is interpreted differently in different world regions according to the perception of future energy markets. This leads to different materials performance targets and the direction and timescales of the materials development programme needed to meet those targets. In this paper, the implications for materials requirements of a fast track approach to fusion development are investigated. This includes a quantification of the overall benefits of more advanced materials: including the effect of trading off an extended development time against a reduced cost of electricity for resulting power plants.

1. EU power plant concepts

In the power plant conceptual studies (PPCS) carried out in the EU recently [1] a range of plants (named Models A, B, C and D) was studied, from near term in physics, technology and materials (A and B) through to advanced designs (C and D). In materials terms, Models A and B assume the use of a reduced activation ferritic/martensitic (RAFM) steel, in particular EUROFER, for the structure of components inside the vacuum vessel. Either using water (A) or helium (B) as the primary coolant, this leads to moderate thermodynamic efficiency (<40%), large size ($R > 8$ m) plants. The more advanced plant designs use silicon carbide composite materials either as an insert in cooling channels (Model C) or as structural material for the internal components (D).

The main differences between the plants models are in the physics assumptions, affecting primarily the recirculating power, and the maximum coolant temperature, affecting the thermodynamic efficiency. Taken together these differences make a significant difference to the calculated cost of electricity of the different models [1], ranging from 5 to 9 €cents/kW h for an early generation plant, then falling to 3 to 5 €cents/kW h in a mature technology. In each case, the lower figure is for the advanced plant, Model D, whilst the higher figure is for Model A.

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2. Fusion development path

In considering the development path that may be followed by fusion, it is important to identify the information that is needed at each stage and how that impacts on the readiness to move to the next stage of development, yielding a critical path analysis of fusion development. This has been studied recently [2] in the light of the decision on ITER siting, in part to determine the route from ITER to commercial fusion power. In this assessment the three fundamental items are ITER, IFMIF and DEMO – a demonstration power plant that pulls together the science and technology information from ITER, and the materials information from IFMIF. Fig. 1 shows a simplified chart of the fusion development path as described further in [2].

3. DEMO

The role that DEMO must fulfil is determined by the fusion development path, which in turn is influenced by the way to optimise the value of fusion as an energy source in a future energy market. Here we will consider a fast track, or just-in-time, approach to fusion development in which the main choice for in-vessel structural materials is RAFM steel [1,2].

DEMO is considered to operate in two specific phases leading at the end of life to reliable operation of a fusion plant. In the first phase, it is anticipated that, due to its novelty, the reliability will be low and consequently the total neutron fluence over this phase will be relatively low, corresponding to 30–40 dpa. The materials requirements for the first phase of DEMO are therefore lower than for a commercial power plant and consequently require shorter testing times in IFMIF than would materials qualification for a power plant. Having addressed reliability issues in the first phase of DEMO, the second phase is assumed to require tolerance to much higher neutron fluences, corresponding to up to 150 dpa, requiring longer testing in IFMIF and further materials development. It is assumed that this proceeds in parallel to the design, construction and operation of the first phase of DEMO.

The following section describes further the reasoning behind a fast track approach to fusion in terms of an optimum route to fusion power and what determines that route. There then follows an

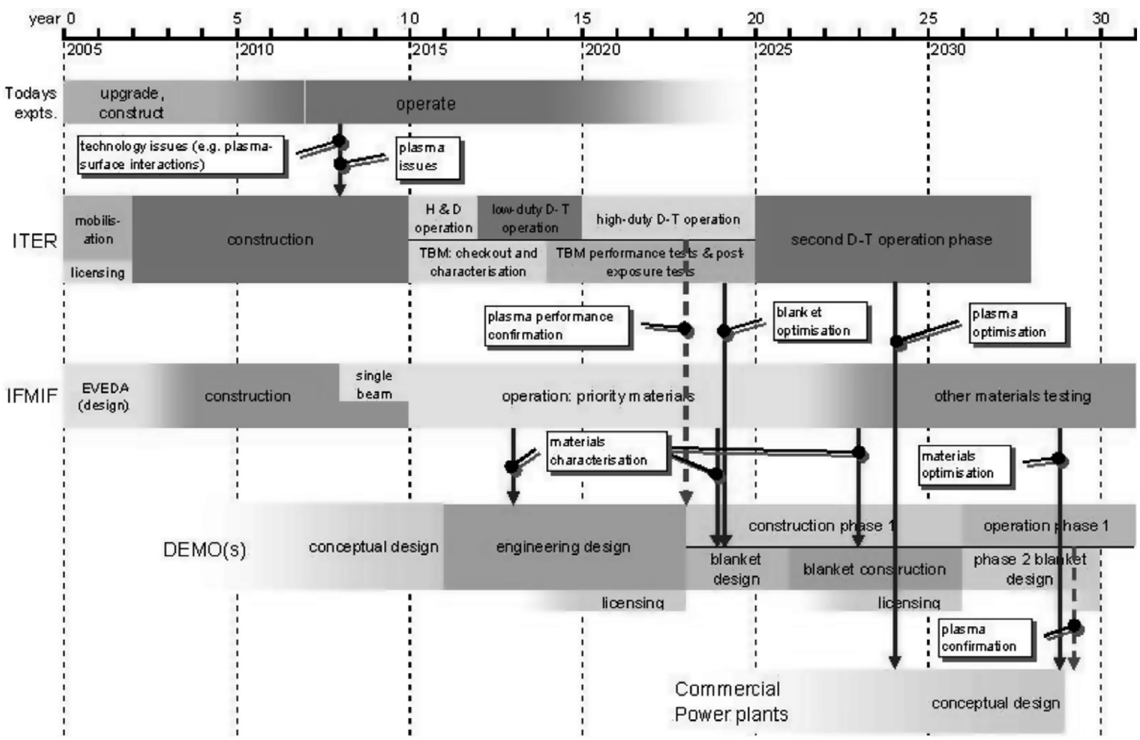

Fig. 1. Illustration of a just-in-time approach to fusion development.

assessment of the value of material advances in the context of that development path.

4. Value of fusion

A further input to the discussion about fusion development is the value of fusion as a future energy source. This has been studied in general terms in [3] and in more detail in [4]. In these investigations, probabilistic decision analysis is used to break fusion development into a number of stages and identify at each decision point what must be done, what are the costs and what are the risks. Finally, results from scenario models are used to determine the role that fusion can make in the future energy market, and the value of that contribution.

Overall this approach highlights that fusion, along with any other major energy option, has the potential to make a significant contribution to an enormous market (presently around $\$10^{12}$ per year and increasing at around 2% per year). This means that the future benefit of fusion, if successfully brought to market, is so large that, even after discounting over the development period, the present value of the potential benefit far outweighs the present value of the development cost. A complete calculation involves estimating the risk at each stage and following multiple paths through the decision tree to give the overall expected net present value, which is substantially positive. This is only one aspect of the value of a future energy option since other aspects such as security of supply arising from diversity of fuels are not captured.

This discussion highlights two aspects of valuing fusion development in this way. The first is that the lower the cost of fusion electricity relative to other systems, the greater the future value. The other is that the longer the development time, the greater the period over which the future benefit must be discounted and so the lower the benefit.

The balance between these two depends crucially on what the cost of electricity from other sources is expected to be, which in turn is highly sensitive to expectations about the nature of the market, particularly the emphasis on pollution and carbon dioxide emissions. It highlights why different emphasis can be given to the fusion development strategy in different parts of the world, depending on the perceived direction of the energy markets. In particular, if the perception is of a low carbon future, in which electricity generation must be largely carbon neutral, the need for replacements for fossil fuel systems (or fossil systems with carbon capture and storage) will drive expectation of higher electricity prices. In this case, the most effective route for fusion development is likely to be the fastest reasonably achievable, with a conservative plant design bringing forward the benefits of fusion and reducing the period over which future benefits must be discounted. Conversely, a more business-as-usual assumption of inexpensive electricity from coal or gas will emphasise more strongly the need to reduce the cost of electricity from fusion, even if that involves a longer development programme with later introduction of fusion into the market. In this context it is of note that the EU now has an established market in carbon emission permits, trading (at the time of writing) in the range 20–30 € per tonne of CO_2, equivalent to adding 2–3 €cents/kW h to the price of electricity from a coal fired plant.

The following data shows an illustrative calculation based around two scenarios: the early adoption scenario in which there is early availability of a near-term fusion plant, at relatively high cost, and the advanced scenario in which there is a more advanced plant available, but not until a later date. Fig. 2 shows the assumed cost of electricity for these plant models (based on the systems studies from [1]), falling with time as a result of further R&D and technological learning.

The value of fusion as an energy option in these two scenarios is then investigated. It is natural to expect that the lower cost system, the advanced scenario, is the more valuable, however its value will be reduced by discounting. The two main issues that affect this are the discount rate and the market price of electricity in which the technology must compete. Fig. 3 shows an example of the ratio in value of the two scenarios for two different values of discount

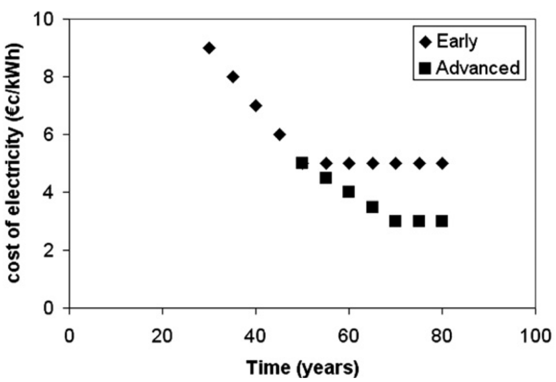

Fig. 2. Assumed cost of electricity in the ‘early adoption’ and ‘advanced’ scenarios.

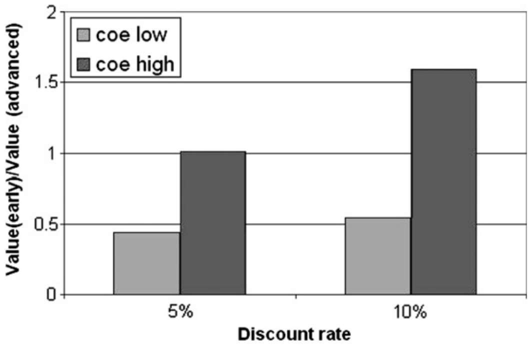

Fig. 3. Relative values of fusion in the two scenarios under different assumptions on discount rate and market cost of electricity.

rate (5% and 10%) under different assumptions of the market price for electricity (6 €cents/kW h or 9 €cents/kW h).

The illustrative calculation shows that at the lower discount rate, it is worth waiting for the advanced plant to be available, unless the electricity price is high in which case the early adoption of the near term plant is marginally preferable. At high discount rate and high electricity price, the early adoption scenario is far preferable to waiting for the advanced plant.

Of course this only serves to illustrate the dependencies and does not provide a convincing qualitative argument. In particular the two scenarios are somewhat extreme, for instance assuming that the early adoption scenario cannot take advantage of a later generation of advanced plants. This would probably happen in reality and would make the early adoption scenario always the most valuable. In general terms, however, an expectation of high market price of electricity coupled with a reasonably high discount rate would tend to favour the early adoption strategy, whereas low electricity prices would favour the advanced scenario.

5. The value of material advances

There are many benefits of advances in materials [5] which include high neutron resilience; high temperature operation; low cost, high performance superconductors, and high heat flux tolerance. Only a few of these can be discussed here. One of the keys to reliable operation of a power plant will be long lifetime for internal components, the blanket and divertor, to allow high availability and reduced electricity costs in a capital intensive system.

The effect of blanket lifetime is summarised in Fig. 4, which shows how a higher tolerable lifetime blanket fluence impacts on the availability of a power plant and hence the cost of electricity. These studies are carried out with a systems code, PROCESS, which models the power plant from the plasma, through the blanket, divertor, coils and conversion cycle to the site and buildings, and in this case assumed a 6 month period required for the blanket replacement, 3 months for divertor replacement. It is clear that a lifetime fluence of above 5 MWa/m^2 is almost essential, 10–15 is desirable but values above 20 give diminishing returns.

Fig. 5 shows a similar assessment for the divertor in which a lifetime of more than 1 full power year seems essential, and 2 or above is highly desirable. In either of these cases the material advances have the potential to reduce the cost of electricity by

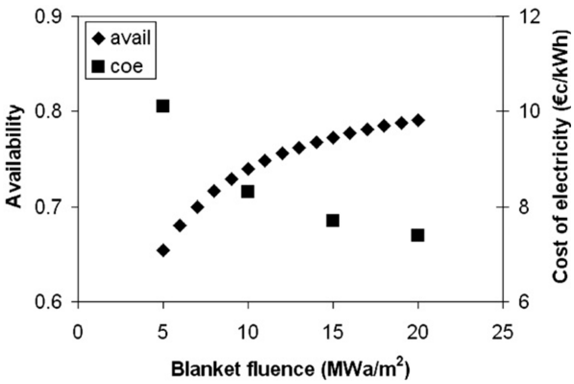

Fig. 4. Increasing the tolerable lifetime fluence of blanket materials increases the overall plant availability and reduces the associated cost of electricity.

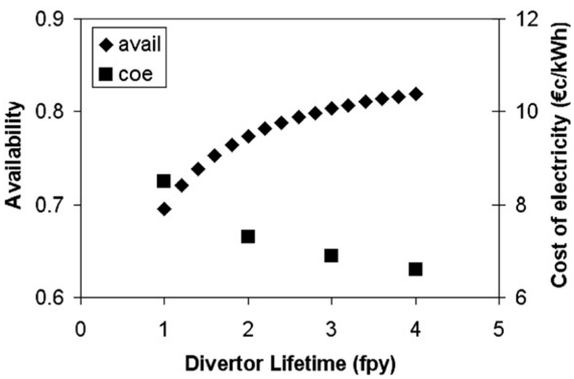

Fig. 5. Increasing the divertor lifetime (measured in full power years) increases the plant availability and reduces the cost of electricity.

around 20%. In the context of the above discussion of the overall value of fusion, this corresponds to a financial value in the region of $10–100 \times 10^9$ € (depending on discount rate and market cost of electricity). This emphasises the enormous value of materials developments.

In addition to the fast track approach of optimising conventional structural and divertor materials, there is the further potential for substituting more advanced, high temperature materials such as silicon carbide composites. Although we have discussed the reasons for concentrating initially on steels, in a fast track approach, there is of course significant potential for further advances in a second generation of power plants to higher temperature operation, approaching 1000 °C instead of 300–400 °C in water cooled steel. Here there is great potential for further reductions in electricity cost, perhaps by as much as 50%. Again this corresponds to an enormous increase in the value of fusion as an energy source.

6. Conclusions

Recent EU studies of fusion power plant concepts and roadmaps to fusion power, coupled to changes in the perception of the future energy market, motivate reconsidering the optimum route to fusion development.

In the context of the EU perception of future energy markets, with strong decarbonisation targets for the energy markets and the introduction of carbon emissions permits, a rapid development of fusion power is increasingly favoured. Given the different perceptions in different world regions, this is likely to motivate different approaches and may cause tension in the international collaborations, in both ITER and the materials programme.

Rapid development of fusion requires a focussed approach to R&D, including that in materials, to concentrate primarily on optimising the most promising early materials. Here those are assumed to be RAFM steels.

Given the size of the world electricity market (around 1×10^{12} €) and expected increases in the future, the potential value of a new energy source is enormous, far greater than the current expenditure on fusion development. As a result, the added value from materials advances is correspondingly large and has a value of the order of 100×10^9 € (although this depends strongly on the discount rate assumed). The fast track approach to fusion presented here depends critically as a first step on a rapid, concentrated, R&D programme on the optimisation of RAFM steels.

Acknowledgements

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