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ECONOMIC CONSEQUENCES OF FUSION MATERIALS DEVELOPMENT

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Economic Consequences of Fusion Materials Development

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Abstract. The programme of qualification and improvement of materials for use in a fusion power station is crucial to the introduction of fusion power into the energy market and power plant studies are used to guide the targets for materials development. It is common to mis-interpret these targets as minimum values that must be achieved for fusion power to be a viable energy source, implying that failure to fully meet these targets will prevent fusion from playing a role in future. It remains important to improve materials properties but this must always be considered in context by an integrated power plant design in which all aspects are consistent. Rather than making fusion an impossibility, different levels of materials performance will lead to a different design in which their use is optimised, for instance compensating reduced lifetime neutron fluence by power density and machine size. Such trade-offs are an economic issue and relatively large variations in materials properties can be accommodated with small changes in overall cost of electricity. The full material impacts are much more complex than just the tolerance to neutron damage, and these must all be considered in a fully integrated way. Of particular importance are the tolerance to heat load, the combined effects of operating temperature and neutron load, which can impact on thermodynamic efficiency, the compatibility of different materials and their phase stability over the characteristic timescale of continuous operation of a power plant.

1. Introduction

An important part of bringing fusion power to the energy market is the development, qualification and improvement of materials [1]; this is the key to maximising the value of fusion's large resource base and its environmental and safety qualities. The approach commonly taken to deriving the targets that should be achieved by the materials programme is to derive them from power plant studies which are optimised against all other parameters. The risk associated with this approach relates to its inflexibility since it implies that failing to meet the targets will prevent the construction of a fusion power station, whereas it may, in fact, only necessitate a small design change. This approach can be most seriously misleading in discussions of the materials properties which are required for DEMO construction to proceed since, depending on the specific view of DEMO, it is likely that required lifetime fluences will be lower in DEMO than in a mature power station.

It is common to mis-interpret the targets for materials development derived from a top-down approach, treating the materials targets as values that must be achieved for fusion power to be an economically viable energy source, implying that failure to fully meet these targets will prevent fusion from playing a role in future. A more useful approach is an integrated and evolutionary one in which materials properties are an important part of the input to power plant design, and not an output. Although the former approach is useful to give guidelines to the materials programme, it is not an appropriate way to set firm targets as there is a possibility that these targets may not be met, or that alternative innovative solutions may be found, and little information is then available as to how important this is. An integrated approach clarifies the economic penalty of not achieving these targets, and sets the materials development programme properly in context.

2. Plant Availability

A crucial aspect of any power plant is its availability, particularly in a system which is capital intensive such as fusion. Modelling of availability in systems codes can be carried out by combining estimates of unplanned unavailability with planned availability calculated from material lifetime estimates and the replacement times. Whilst there is still considerable uncertainty in these parameters, we can nonetheless investigate their relative importance and the effects of e.g. tolerance to neutron damage on the design of an optimised machine.

The cost of electricity expected from a fusion plant has previously been shown to scale approximately with $A^{-0.6}$, where A is the plant availability [2]. The scaling is not as strong as if the costs were entirely due to capital expenditure, as there are costs of replacement components, as well as other costs associated with Operation and Maintenance of the plant. Nonetheless, availability is one of the most important determinants of the cost of electricity from a future fusion power station – more important than many parameters normally given strong emphasis such as the normalised plasma pressure.

In the PROCESS systems code, a model of availability is included which assumes a regular replacement of the divertor, typically every 2 years, and blanket replacement with a lifetime that depends on the neutron tolerance of the materials chosen [3]. In addition, there is a substantial allowance for unplanned availability of each of the major systems. A typical lifetime lies in the range of 5 to 10 years. The shutdowns are then aligned so that the actual lifetime of the blanket is an integral number of divertor lifetimes, in order that the larger shutdown for blanket replacement also includes a divertor shutdown. In what follows, each data point is a fully consistent conceptual fusion power plant design, with restricted divertor heat load – the actual design is chosen from the family of possibilities by minimising the projected cost of electricity. The starting point for the examples given here is the technology of the PPCS plant model C [4]. Whilst changing this assumption would change the values of the outcomes it leaves the main conclusions largely unchanged.

Figure 1 shows the simple relationship between the cost of electricity and availability, in a calculation where availability is an **input**. Because of the capital intensive nature of the fusion power station, the cost of electricity falls as the availability increases. Figure 2 shows another aspect to this, which is that deliberately driving up the machine size, when the full availability model is used, increases the plant availability by reducing power densities and extending in-vessel component lifetimes.

The effect of availability on costs has now become more complex. If the lifetime of in-vessel components is short, for instance because a particular material chosen for its design is not sufficiently resilient to neutron damage or surface erosion then the increased cost of increasing machine size can be counter-balanced by increased plant availability, such that the larger machine actually produces electricity at a lower cost. This trade-off between availability and capital cost is one that is often overlooked, but can be important, especially if neutron resilience for a class of materials chosen for constructing a power plant is found to be low. It is therefore very important to allow the machine design to change and adapt when studying the effects of materials properties on economics.

The optimum in the balance between increasing capital costs and increasing availability depends on the materials properties and also on the length of shutdown needed to change the components. In the example given in Figure 2, the unavailability due to blanket replacement is only around 10% (with a 100 dpa lifetime neutron dose and a 6 month shutdown for combined blanket/divertor replacement) so in fact it remains the case that the smaller machines produce cheaper electricity. However, if the material chosen has a lower resistance to neutron damage, or the blanket replacement time is longer, it becomes increasingly favourable to move to a larger machine with reduced power density.

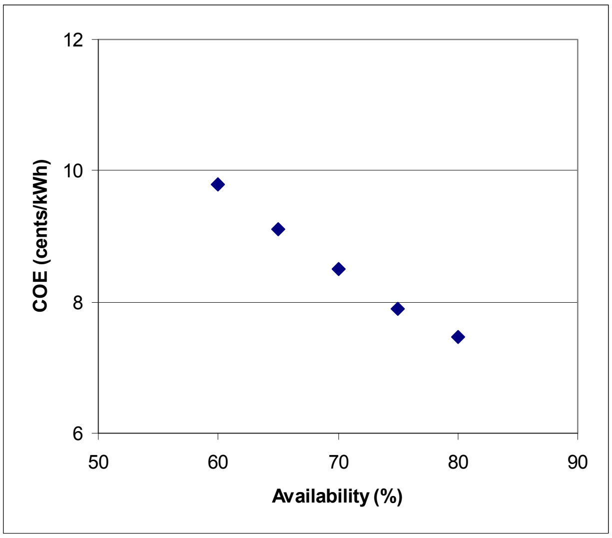

Figure 1: Cost of electricity is a strong function of availability. In this figure the availability is an input, not modelled with the full availability model.

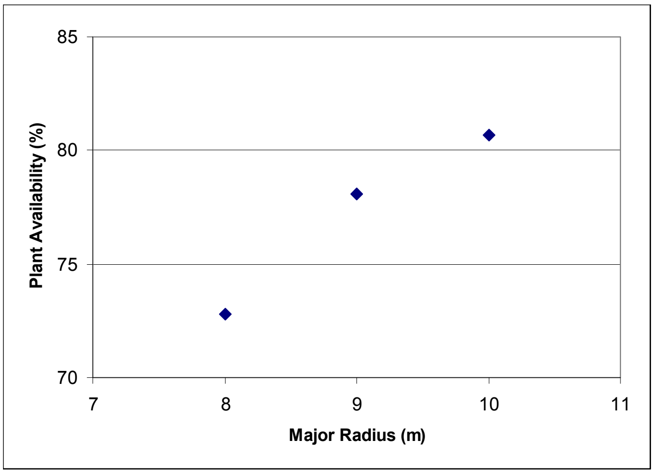

Figure 2: When the availability is fully modelled, an artificial increase in the major radius also increases the device availability, by lowering the power densities and neutron flux, extending the lifetime of internal components.

Figure 3 illustrates the effect of improved economics for larger machines by assuming a very low neutron tolerance (20 dpa), in which case the results with modelled availability suggest a larger machine size is preferred. This is emphasised further by the data labelled "long shutdown" in which a very low neutron tolerance and a very high shutdown time are combined. Whilst these are extreme cases, they serve to illustrate how, particularly at low materials performance, it is possible to trade off reduced performance against other design features in order to reduce the penalty paid.

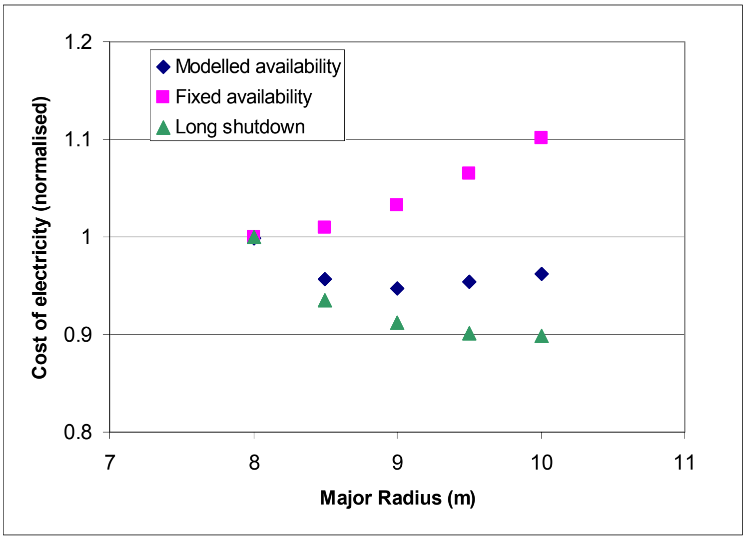

Figure 3: The cost of electricity variation with machine size differs when the full availability model is used. Here a very low tolerance to neutron damage is assumed (20 dpa). If availability is fixed, the costs purely increase with machine size, however modelling the availability shows that, in reality, a reduced cost of electricity is to be expected. The advantage of increasing radius becomes more pronounced in the case of an assumed long shutdown for the blanket exchange, in which case the gain in availability outweighs the increased capital costs even up to 10m major radius. In this case the actual cost of electricity, without normalisation, is higher than in the other cases.

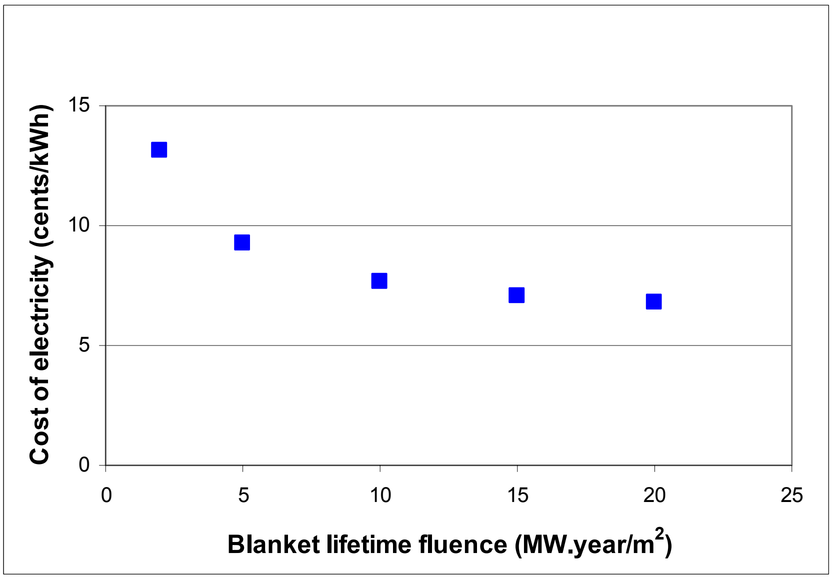

Figure 4: Cost of electricity variation with the assumed blanket fluence (quoted here in MW years per m^2; for steel 1 MW.year/m^2 corresponds approximately to 10 dpa).

Overall then, the negative consequences of poor materials performance can, to some extent, be offset by changes in machine design. The result is that the economic penalty of reduced materials performance can be less than expected on the basis of a fixed plant design.

In the calculations given in Figure 4, the blanket fluence is shown down to very low values equivalent to 20 dpa, far lower than are normally considered credible. The results show that a factor of 5 reduction in blanket lifetime fluence leads to an increase in the cost of electricity by almost a 60%. This data suggests that the often cited targets of 100-150 dpa for lifetime blanket fluence are sensible, but that increasing this to 200 dpa or above has reduced benefits. Although the ability of fusion to compete in an energy market depends on its economics relative to other sources, whose future costs are uncertain, it appears that if we took a reasonable target of costs below 10 cents/kWh, this could be achieved with a lifetime fluence equivalent to around 50 dpa (although this is inevitably a very uncertain requirement). The perception of such a target will depend on the market in which the power stations must compete, however it appears that 50 dpa may be good enough for a first generation of power station, and therefore easily enough for DEMO, but we must, of course, strive for greater performance.

3. Divertor

A crucial part of the availability modelling is that the shutdowns for divertor and blanket replacement are forced to coincide, when appropriate, to maximise availability. For instance if the plant has a two year divertor lifetime, then even though a blanket might tolerate 7 years of operation, it is replaced after 6 years to avoid unnecessary extra shutdowns. This has two important effects in looking at the economic effect of materials. Firstly, the reduced power density of larger machines extends the blanket life but may not extend the divertor life. If it does not, then there is no gain in availability until the potential blanket lifetime is extended by a full divertor lifetime. This leads to a discontinuous behaviour in the availability modelling, unless the divertor lifetime is also extended when power density reduces. Secondly, at very low tolerable blanket fluence, the blanket lifetime may fall to around one divertor lifetime or less, so the behaviour at low fluence is qualitatively different – here the divertor may be exchanged unnecessarily early, so there is greater advantage in extending the blanket lifetime by increasing device size.

This practical outcome of the dependence of divertor lifetime on overall power density is a crucial one in modelling the economic impact of materials development. In the calculations above, the divertor heat load, and its lifetime was held constant so the beneficial effect of increasing size to reduce the penalty of reduced materials performance was restricted to the blanket. Relaxing this constraint would give further benefits so further studies of the divertor lifetime remain very important.

4. Thermodynamic Efficiency

Another key factor in the relationship between materials properties and economics lies in the coolant temperatures, and thermodynamic efficiency of the plant. The operating temperature of materials in a fusion device is determined by a complex interplay of effects including the material strength and difference in neutron damage at different temperatures. These restrictions do not merely serve to drive operation towards low temperatures, indeed it is very likely that the materials degradation with neutron irradiation will be less severe at increased temperatures.

There have been many studies of the effect of improved thermodynamic efficiency on the economics of fusion power stations; in the PPCS this was the primary advantage in the more advanced plant models, substantially more important than the assumed advances in plasma performance. Figure 5 shows an illustrative example of how the cost of electricity varies with thermodynamic efficiency.

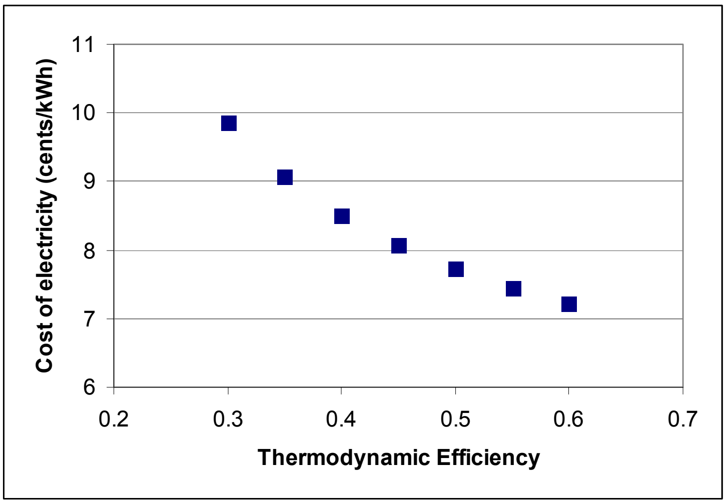

Figure 5: Cost of electricity variation with the thermodynamic efficiency. In these calculations the availability is fixed at 75%.

5. Relationship to Fusion Materials Development

The development of fusion materials is inevitably more complex than implied by the simplistic modelling described above. For instance, although not explicitly assumed, it is implied that engineering properties of materials vary smoothly with the parameters characterising the fusion environment where they are expected to operate. In fact this is not generally the case.

Fusion steels suffer irradiation embrittlement, in other words, a marked increase of the ductile-brittle transition temperature (DBTT), particularly at relatively low irradiation temperatures (such as 300 Celsius). The DBTT tends to increase rapidly at low neutron dose, and only slowly, if at all, at higher doses [5,6,7]. This adds a complexity which is difficult to include in the earlier assessments.

The coupling of neutron tolerance to other design parameters can also be of great importance, for example steels exposed to irradiation at increased temperature, e.g. above 400 Celsius, may see almost no embrittlement effect [5]. This coupling greatly complicates the assessment of the materials impact on power plant design since the outcome for the materials is very dependent on specific details of the plant design. Such complexity can also result from further non-linear effects such as phase transitions, including the recently explained reduction of mechanical strength of steels at temperatures above 500 Celsius [8,9].

What are the implications of these observations for fusion power? Firstly it is essential to have fully quantitative knowledge of materials properties in a fusion environment. Secondly, there is a pressing need for innovative thinking and the development of an integrated approach to fusion power plant designs, based on advanced engineering, research in new materials, and the development of operational modes for a fusion power plant. A combination of these factors, rather than any of them individually, will ultimately decide the case for fusion as an economically competitive means of power generation.

6. Conclusions

Materials properties should be used as inputs to power plant studies, as well as using power plant studies to derive ultimate targets for the materials programme. This gives different insights into the coupling between materials performance and economic performance of fusion. The example of structural materials with low tolerable blanket fluence shows that larger machines can be the economic optimum, when plant availability is properly taken into account.

The question of what targets we should aim for in the materials development programme, and how to interpret those targets from an economic perspective, is addressed. In particular, the target of around 150 dpa for fusion steels should not be seen as the minimum value necessary for fusion to be realised but, in these studies, is more like a maximum level beyond which there is little further benefit.

Conversely, the role of fusion in the future energy market may depend critically on costs so even relatively small changes in fusion costs may have a substantial impact on future market share.

Research is presently at the point where advances in materials properties may substantially reduce fusion costs, for instance if a material with an operating limit of 20 dpa were improved to reach a level of 100 dpa, cost of electricity estimates would fall by around 60%, largely as a result of increasing availability.

Although the effect of reduced materials properties can be, to some extent, ameliorated by design, materials research remains an absolutely crucial part of producing an economically competitive energy system. The materials development work should be more integrated into power plant designs and the wider fusion programme, in order to optimise the fusion development programme as a whole.

7. References

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