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Design issues for fusion commercialisation

R. Kembleton[a], W. Morris[b], G. Federici[a], A. J. H. Donné[a]

[a]EUROfusion PMU, Boltzmannstr.2, Garching 85748, Germany
[b]CCFE, Culham Science Centre, Oxfordshire OX14 3DB, United Kingdom

***Abstract*— The EUROfusion Roadmap for fusion research was recently updated and describes a clear set of missions and associated goals on the route to commercial fusion electricity. Beyond ITER, the main target of the programme is the development of DEMO, a fusion technology demonstrator which will produce substantial net electrical output, breed its own fuel, and demonstrate supporting technologies such as automated remote handling systems aimed at high availability. Work on DEMO has already proven extremely valuable in identifying the substantial design integration issues and system interdependencies which uniquely complicate fusion power plant design. However, the uncertainties which arise from the low Technology Readiness Levels of fusion systems mean that DEMO must be robustly designed with substantial margins in performance, and while it will demonstrate the technological feasibility of an integrated fusion power plant, further work will be required to refine the concept towards attractive commercialisation.**

Under EUROfusion Mission 7, work is turning to the wider problems of how fusion-produced energy can be turned into economically-viable electrical energy. A fusion power plant is a uniquely-challenging environment and requires specialised technologies: unless the materials and technology can either find crossover applications outside fusion or ways to dramatically reduce costs as they are scaled to full commercial roll-out, fusion will probably always appear to be expensive.

This paper outlines the EUROfusion approach to solving these problems. It describes the problems faced in engineering a fusion power plant; supply chain and procurement issues to be solved; and suggests ways in which fusion power might be made cheaper.

***Index Terms*—Fusion power generation, Fusion reactor design, Tokamaks**

I. INTRODUCTION

THE updated EUROfusion Fusion Research Roadmap [1] describes a clear set of research priorities aimed at the overall mission of “Demonstrating fusion electricity production by the middle of the century”. It provides a coherent EU physics and technology research programme with clear goals and indicative dates for their achievement. The main target within this programme is the development of DEMO, a fusion technology demonstrator intended to not only produce substantial net electrical output at the hundred of MW level, but also to sustainably breed its own tritium fuel and demonstrate all supporting technologies aimed at high availability such as automated remote handling and plant protection systems. A complete plant layout also allows assessment of the radiological and regulatory aspects of fusion power [2].

The timescales of the DEMO programme are intended to build upon the development of ITER, making use of lessons learned and industrial involvement such that there is a continuation of interest in fusion from industry.

More widely, the demand for electricity is forecast to grow dramatically, possibly doubling in the next 20 years [3]. Modelling shows that even with substantial energy storage and continental interconnects to allow the smoothing of intermittent generation from renewable sources, some level of baseload generation will still be required to make power systems as reliable as we have come to expect [4] [5]. Such baseload generation must be carbon free, leaving a role for fusion power. Scenarios for future energy markets involving fusion power have been studied which show a potentially substantial role [6].

II. ACHIEVING COMMERCIAL FUSION POWER

Having studied the market and social demands for fusion power, it is then necessary to examine how such demands may be met. The economics of fusion power are non-trivial but have previously been examined for DEMO-like devices during the European Power Plant Conceptual Study [7]. To start such an analysis, a plant concept is first required, covering many plant systems and site layout, to examine the drivers of costs and performance (Fig. 1). This concept can then be used as a framework for identifying options for reducing costs and assessing the impacts of incorporating new technologies on the whole plant, what we might term *integration costs*. It also allows consideration of the transferability of data generated by ITER and DEMO to the concept: is the physics scenario the same? Are further technological developments or test devices required? What additional materials are needed?

EU-DEMO is fundamentally intended to be a relatively low-risk power plant prototype based on the best available current data and employing performance margins so that there is some confidence it can achieve its high-level operational targets. It is aimed at closing many technical gaps simultaneously and is closely tied to the ITER timeline, as ITER is intended to provide the physics basis. Taking these constraints into account, DEMO

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R. Kembleton, G. Federici, and A. J. H. Donné are with EUROfusion PMU, Boltzmannstr.2, Garching 85748, Germany. R. Kembleton is the corresponding author: richard.kembleton@euro-fusion.org

W. Morris is with Culham Centre for Fusion Energy, Culham Science Centre, Oxfordshire OX14 3DB, United Kingdom

is not aimed at a design which will provide competitively-priced electricity, which we should not in any event expect from a first attempt to integrate fusion technology into a coherent whole.

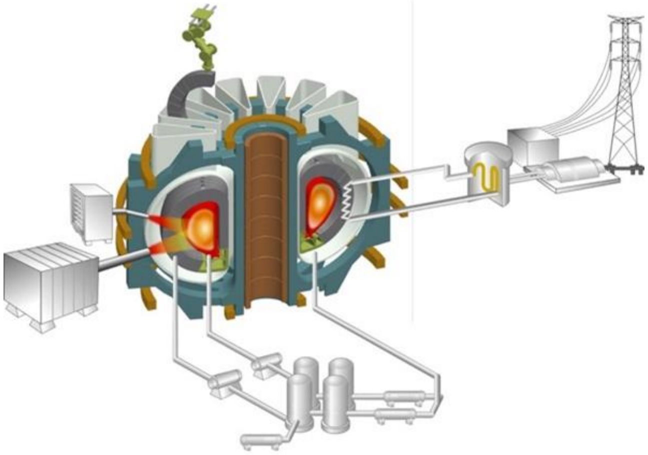

Fig. 1. A conceptual fusion power plant with auxiliary systems, including maintenance, heating and current drive, tritium breeding, and balance of plant. Consideration of all such systems is important when determining the plant economics. Image: EUROfusion

The DEMO project is aimed at studying the real engineering design problems associated with such integration. As confidence grows in the technical readiness levels and performance limits of the systems studied further optimization can be carried out. Nevertheless the underlying integration issues only become obvious as the design matures and trade-offs must be solved. Some of these include the interaction between the approach to remote handling of the in-vessel components and the poloidal field (PF) coil placement and a subsequent impact on the plasma stability and shaping; the placement of limiters for first-wall protection and their impact on tritium breeding from the breeder blanket lost to provide the space; the choice of primary coolant on pipe and building layout; and the impact of the choice of plasma scenario on the exhaust and fueling cycle. These problems can only be effectively solved in an integrated way as they are interdependent, and so the plant design must iterate progressively towards overall consistency and performance.

Assessing a viable path to commercialization is complicated by the role of nuclear regulation in the process. While it is relatively inexpensive to build a new tokamak which does not handle tritium and is not required to generate electricity, the experience with nuclear facilities in recent years is that the process is complicated, slow, and reactive rather than proactive – that is, the regulator will provide advice and feedback on a given plant design, but will not provide guidance for turning a concept into a design. This is further exacerbated by the large uncertainties in fusion technology, where further research is required into tritium breeding systems, remote handling, plasma facing components, neutron-damage resistant materials, etc. There is an open question as to whether elements of these technologies have crossover applications in other industries, which would aim their development for fusion, and to what extent they can be developed and qualified without a fusion-like neutron source for testing in representative operational environments before incorporation into a power plant.

A. *Fundamental design considerations*

The target performance measures have a strong impact on the basic machine parameters (Fig. 2). In this case – based on EU-DEMO assumptions, but a similar analysis can be performed for different geometries such as spherical tokamaks or stellarators – it is possible to produce some fusion power in a small device. Once 50-100MW of fusion power are reached (depending on assumptions about operational availability) then external tritium is not available in sufficient quantities [8] and the machine must breed its own fuel. (100MW D-T fusion requires 5.5kg of tritium per full-power year; approximately 1kg per year is probably reliably available.) This both results in a sudden jump in size, due to the need to fit a breeder blanket on the inboard side, both adding to the radial build directly and pushing the plasma into a lower-field region further from the coils, and a dramatic increase in the plant layout complications as now the relevant plant for handling a complete fuel cycle must be included. In addition, to produce enough tritium, as much of the interior of the machine as possible must be available for breeding, and effective remote handling systems for regular replacement must be developed. The complexity, and hence cost, of the plant increases.

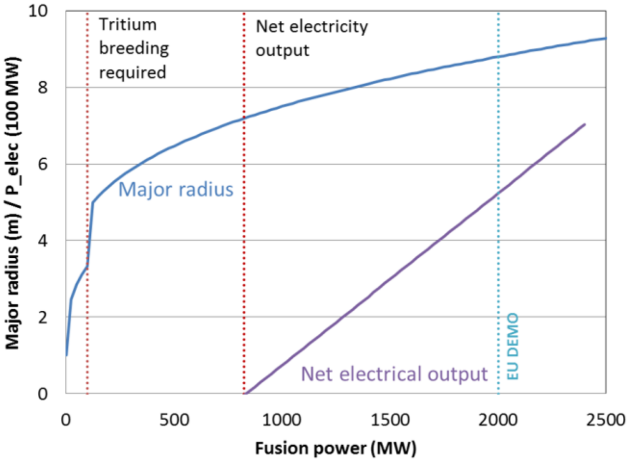

Fig. 2. Schematic plot of major radius (R_0) versus fusion power and net electrical output using EU-DEMO-like assumptions. At low power tritium can be externally supplied; once tritium breeding is required, the incorporation of a blanket on the inner side of the plasma pushes the plasma into a lower-field region and also adds to the radial build, pushing R_0 up significantly. In order to meet the recirculating power demands of the plant, at least 800MW of fusion power is required.

If one wishes to now produce electricity, the primary coolant from the breeder blanket must be coupled to a steam generator and then to turbines. This becomes a possible vector for tritium to migrate out of the plant and so, as well as the increase in complexity from the generating systems there are additional regulatory and safety concerns.

In most large engineering projects, systems can be developed in relative isolation and brought together when sufficiently mature. In fusion, generating neutrons to give a fusion-relevant environment for component testing is not trivial, and it is likely that the best way of doing it is to actually build a reactor –

although this relies on the availability of the components you wish to test. The overall upshot is that a first prototype fusion power plant is likely to have to be very conservative in its assumptions to have confidence in both operational success and regulatory approval, making it appear highly commercially uncompetitive regardless of the long-term fusion opportunities.

B. Aspect Ratio

Low-aspect ratio tokamaks such as spherical tokamaks (STs) have higher β limits, with the maximum β given by [9]

$$\beta_{\max} = 0.072\left(\frac{1+\kappa^2}{2}\right)\varepsilon$$

where κ is the plasma elongation and ε is the inverse aspect ratio, $1/A$. Low aspect-ratio tokamaks also have higher vertically-stable κ. However, for a given major radius and maximum magnetic field available on the TF coils, the higher β is offset by the lower field in the centre of the plasma due to the larger minor radius. The impact of this is worse for smaller machines, as the thickness of vacuum-vessel/shielding/breeder does not scale with device size. The overall effect is that the absolute pressure in the plasma, and therefore the fusion power density, is similar and so the total fusion power scales with the volume of the plasma and not the aspect ratio.

However, there are two potential advantages to low *A*. The first is that if one removes the breeder blanket on the inboard side (although retaining sufficient shielding to protect the magnets), the plasma is moved back into a higher-field region with an accompanying improvement in performance. A lower *A* means that fewer of the fusion neutrons are lost to the now non-breeding center column -- ~17% of the neutrons at *A*=2, compared with ~23% at *A*=3. This means that it may still be possible to get the tritium breeding ratio (TBR, tritium made/tritium burned) sufficiently above one to allow the device to fuel itself. The second potential advantage, especially when looking at economic electricity generation, is that STs tend to have higher self-driven (bootstrap) currents, reducing the requirements for external current-drive and thus increasing the overall plant efficiency (net electrical power over fusion power). However, for a practical fusion technology generator such as DEMO, it is still best to operate in the region where most data are available to avoid also being a physics experiment: this means an ITER-like plasma at *A*=3.1.

C. Reliability

Ultimately a fusion power plant needs to be a reliable source of electricity generation. Any risk of unplanned downtime, or particularly any off-normal event which has a risk of damaging in-vessel components and requiring a shutdown for inspection and replacement, will mean that prospective operators will require a risk premium on top of the nominal cost of electricity to offset their capital risk. Fig. 3 shows the impact on cost of electricity produced by a plant taking into account a risk premium for the possibility of significant unplanned downtime or damage caused by e.g. a plasma disruption.

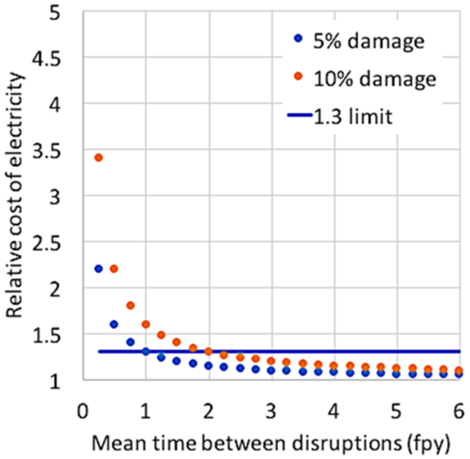

Fig. 3. Plot of relative cost of electricity (compared to nominal cost) demanded by an operator to offset risk of loss of income/capital losses caused by off-normal events or other unplanned downtime. The two curves represent a 5% capital loss (e.g. a loss of 1 year of operation in a 20-year lifetime power plant) and a 10% capital loss (as above, but with e.g. significant damage to in-vessel components). The horizontal line represents a 30% increase in cost of electricity over the nominal forecast cost, at which fusion penetration of future energy markets is almost non-existent **[6]**.

Taking the more conservative 5% case, assuming an availability during normal operation of 70% (including maintenance operations to replace blanket and divertor, and inter-pulse down time), in order to avoid significant additional cost risks there needs to be an expected mean time between disruptions of 3-4 full power years (fpy), meaning every 4-5 years of operational time (the expected lifetime of the blanket, in any event). For EU-DEMO, with a two hour pulse, this means that the expected failure rate should aim to be less than 1 in every 15,000 pulses. The ITER disruption management plan allows for a disruption rate of 1 in every 200 pulses, two orders of magnitude higher than that which could be tolerated in a fusion power plant. This is, admittedly, something of a worse-case scenario where an unplanned shutdown event causes significant down time and/or damage, but it underlines the requirement for a fusion power plant to use well-understood and reliably controllable modes of operation. A robust design point contributes to cost savings.

Given that all in-vessel systems will be contaminated by tritium and other radionuclides from neutron irradiation, maintenance must be carried out robotically, almost certainly autonomously with multiple systems for maximum efficiency. The removed components must be stored in hot cells until recyclable; these hot cells are expensive buildings and so the quantity of stored waste must be minimized. Design options which eliminate remote handling (RH) operations to the greatest extent possible, through aligning component lifetimes and simplifying the movement of RH systems around the plant, for example, must be considered from the outset and are vital to the economics of a power plant.

D. Additional considerations

Being principally still a research project, fusion supply chains are not well established. Identifying crossover applications of fusion and related technology – including development tools, computer modelling, manufacturing and material joining techniques, etc. – would help to secure relevant supply chains and allow further development of such technology without the reliance on fusion funding.

Component designs must be allowed to be influenced by commercial concerns, rather than the best tolerances that can be achieved: they must be “designed for manufacture”. More work is required on what tolerances can be permitted inside a tokamak. It is foolish to think that blanket segments can be aligned to millimeter precision, for example, but what is permissible? Can we develop innovative construction techniques that impact construction logistics? For example, if segmented superconducting coils could be manufactured, this would allow factory construction of coil segments in bulk and remove the need for coil-winding facilities on-site, and would also simplify the assembly of the device. Can blanket segments be designed to allow removal of breeder material and then crushing of the remainder to reduce storage requirements, or for easier disassembly to the same end?

Finally, must fusion follow the same regulatory approach as fission? Lessons are being learned from ITER and in the EU-DEMO dialogue with regulators, but ultimately more data are needed to demonstrate that the risks are different and fusion should be treated more specifically. A faster component and material qualification cycle would greatly benefit fusion as the technology is developed, but this requires an early burning-plasma machine to be sufficiently flexible to allow testing of components whilst also demonstrating operation of a complete set of power-plant relevant technology.

Some of the issues where further thought is required between DEMO and a commercial fusion power plant design are summarized in Table I. Commercialisation requires significant scale-up and cost reduction of supply chains that already exist at lab-scale to supply “one-off” products. Given the lack of fusion-relevant test environments, there is also no well-developed prototyping cycle. In addition, the move from fusion as a research project to an industrial project requires very different management and design skills from the current lab-based research environment.

E. *Impact of unit size*

While there are fusion plant concepts which rely on speculative technologies or physics regimes, these are relatively high-risk due to the paucity of underlying data justifying the operating assumptions. There is also a high chance that as integration proceeds, the designs encounter the same size-driving issues as EU-DEMO has already identified. In particular, the step to nuclear operation requires many levels of redundancy and safety to be considered and demonstrated with operational data, making poorly-characterised regimes especially cumbersome. It is also the case that among the main drivers for the costs of a fusion power plant are the magnets and the buildings: an approach relying on many small tokamaks sharing services such as RH and balance of plant would be extremely complex, and without a detailed plant layout and building design it is unreasonable to claim that smaller or modular fusion approaches are *a priori* cheaper. The overall incentives favour improving manufacturing logistics and reliability over driving down the nominal device size at the expense of these things.

III. CONCLUSIONS

TABLE I
FUSION SUPPLY CHAIN STATUS

Element	Status
Supply of materials	Many materials in development at lab scale or not produced in bulk (steels, 10s of tonnes)
Formation of material	Manufacturing methods in development at lab scale; joining technologies require nuclear qualification
Logistics	Some components too large to transport
Supply of skills	Being built up with industrial involvement
Supply of funding	Political
Design readiness	Integration of plant systems incomplete; initial work on plant layout carried out; no consideration yet of logistics of build
Quality Control/Inspection	Specifications and manufacturing stream not yet settled
End of life	Separation of waste in consideration; design not yet finalized

Any “next step” nuclear device will require extensive engineering and materials development before it can become a reality. Moving away from where most data lie increases project management risks and uncertainties in timescales. It is also impossible at this stage, before the demonstration of so much critical technology in an operational environment, to promise that any one approach is cheaper than another without significant engineering evaluation. Moreover, it is very difficult to have breakthrough developments without a range of experimental facilities to provide data allowing fair judgement on how new options meet the needs of commercial fusion power.

However, maintaining a wide range of conceptual reactor designs is very useful for assessing potential routes to commercial fusion, but achieving any of them will require a programme of engineering development and testing to demonstrate actual performance suitable for nuclear regulatory approval. Such detailed engineering development will always appear as if it is lagging behind state-of-the-art concepts.

Fusion development requires new materials, technologies and manufacturing techniques, the development of which should help to cultivate new industries and supply chains. Such crossover applications will help to make fusion economic but ways must be found to keep industry excited in the possibilities of fusion.

Cost reductions in fusion will partly be found in a focus on the scaling to mass production of fusion components and designing them in the best way to make this possible. This is a detailed engineering task which can be explored on almost any basic conceptual framework: the important step is beginning the integrated design of systems to identify critical manufacturing steps. This is the stage that EU-DEMO is currently at.

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