Design issues for fusion commercialisation

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***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 and materials. It will be important to find crossover applications outside fusion and other ways to ensure reduced costs as they are scaled to full commercial roll-out.

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 can be made commercially attractive.

***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 [2], a fusion technology demonstrator intended to not only produce substantial net electrical output at the hundreds 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.

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, as is fusion. 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 the 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. 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 or alternative 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 that 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

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provide critical input to the design and operation. Taking these constraints into account, DEMO 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.

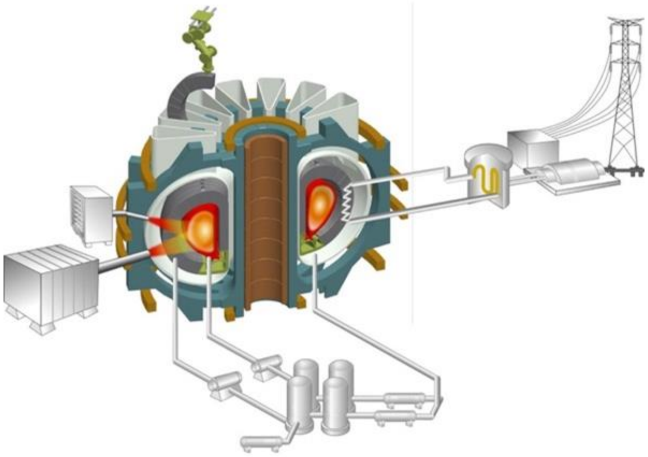

Fig. 1. A conceptual fusion power plant with auxiliary systems, including maintenance, heating and current drive, tritium breeding, and balance of plant. Consideration of all such systems is important when determining the plant economics. Image: EUROfusion

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 especially as it varies from nation to nation. 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. Since the hazards associated with fusion are rather different than from fission, it is possible that alternative regulatory approaches could be developed.

A. *Fundamental design considerations*

The target performance measures have a strong impact on the basic machine parameters (Fig. 2). In the case presented here – based on EU-DEMO assumptions, but a similar analysis can be performed for different geometries such as spherical tokomaks or stellarators – it is possible to produce some fusion power in a small device. The present availability of tritium [8] means that realistically only small-scale or short-duration (low duty-cycle) fusion power can be produced without the machine breeding 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 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. Furthermore effective remote handling systems for regular replacement must be developed due to the shorter lifetimes of components exposed to high neutron fluence associated with higher fusion power for longer times. The complexity, and hence cost, of the plant increases. Self-sufficiency in tritium production is a critical gap from ITER to a power plant, and there are still many unknowns in how this can be achieved. However achieving this is considered part of the Roadmap research programme, rather than a cost risk which will apply to commercial power plants. We believe that while the breeder blanket and associated systems will have a substantial cost, there are ways in which these can be reduced. Work is also taking place within the EUROfusion programme to assess the drivers for e.g. blanket manufacturing costs and how the design can be changed to reduce these.

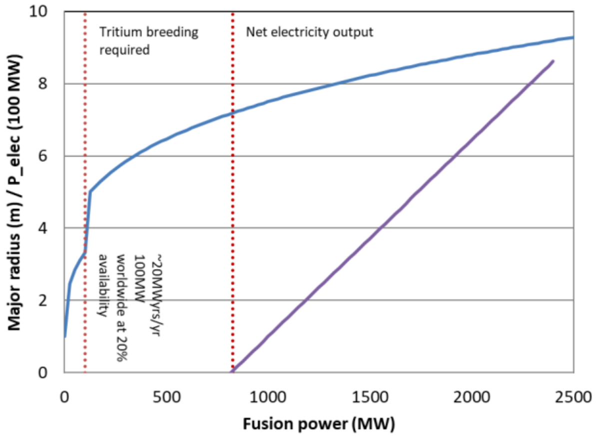

Fig. 2. Schematic plot of major radius (R_0) versus fusion power and net electrical output using EU-DEMO-like assumptions. At low power (e.g. below around 100MW at 20% availability worldwide) tritium can be externally supplied; once tritium breeding is required, the incorporation of a blanket on the 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 in this model.

If one wishes to now produce electricity, the primary coolant from the breeder blanket must be coupled to a generator and then to turbines. EU-DEMO assumes the use of steam turbines to make most use of existing technology. Permeation into the steam 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. Mitigation factors such as anti-permeation coatings are under development.

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 (rather than just materials[1]) 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 may have to be very conservative in its assumptions to have confidence in both operational success and regulatory approval, making it appear commercially uncompetitive regardless of the long-term fusion opportunities. This implies that it is important to work on the path to commercially-attractive fusion plants in parallel, as recognized in the European Roadmap.

B. *Aspect Ratio (A)*

The approach adopted by EUROfusion is to design DEMO with a geometry where the bulk of the experience exists and where it will be directly enhanced by ITER and the majority of currently-available tokamaks, including the upcoming JT-60SA. This implies an aspect ratio close to ITER's, A~3. There is some interest in the community in exploring lower A in parallel to see if the potential advantages can be applied, and some of those features are outlined here.

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 directly with the aspect ratio (although lower A also allows *e.g.* higher elongation).

However, it is possible that one can remove the breeder blanket on the inboard side (although retaining sufficient shielding to protect the magnets): the plasma is then 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/fusion power). It will become clearer in time with further evaluation, particularly of the neutronics and remote handling approaches, whether low A options are credible alternatives.

C. *Reliability and availability*

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 are likely to 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.

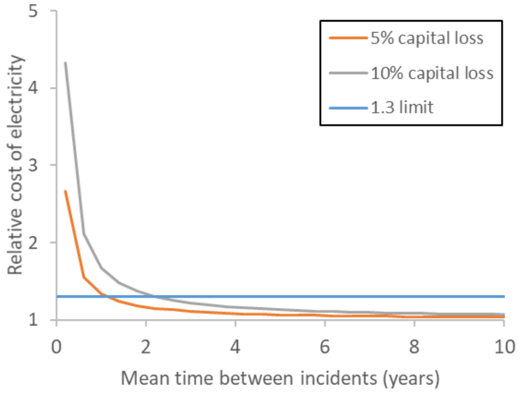

Fig. 3. Plot of relative cost of electricity (compared to nominal cost) demanded by an operator to offset risk of loss of income/capital losses caused by off-normal events or other unplanned downtime. The two curves represent a 5% capital loss (e.g. a loss of 1 year of operation in a 20-year lifetime 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 based on commercial competition 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 by the end of operation. 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

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[1] For materials testing there is a strategy being implemented in Europe via IFMIF-DONES [10], test reactors, and other approaches.

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 simultaneously for maximum efficiency for a power plant. While it is sufficient for DEMO to demonstrate the maintenance operations for systems individually, a power plant must be laid out allowing simultaneous operations. The removed components must be stored in hot cells until recyclable; these hot cells are expensive buildings and so the quantity of stored items must be minimized. These items are not yet waste: the intention is that much of the material is recycled and this should also be a goal for power plants. 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 and commercial readiness*

Since fusion is principally still a research project, fusion supply chains are not well established, although some major steps have been taken for ITER, for example the large-scale production of superconducting wire. 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. These will not alone make fusion commercially viable, but they reduce the need for the current fusion research programme to carry out all technology maturation work and supply-chain development alone. They also help industrial engagement by showing short-term benefits to close involvement with a high-tech research programme.

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. For example it is unrealistic to think that blanket segments can be aligned to millimeter precision, and retain that alignment through many thermomechanical cycles, 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?

It will also be important to reduce overall complexity, for example by limiting the number of sub-systems such as different heating and current drive methods, and increasing standardization of parts (for example monoblocks in the divertor, and internal elements of blanket segments) to take best advantage of bulk manufacture. In this way – designing for low cost from the outset – there may be some deviation from a design optimized for physics performance or coolant flow, but the overall capital cost reduction may outweigh these concerns: more detailed analysis of acceptable tolerances and deviations and their impact on plant output is required.

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
Supplier engagement	Tier 1 (customers/stakeholders) consulted Tier 5/6 (basic materials suppliers) initial engagement Rest of supply chain not yet engaged
Logistics	Some components too large to transport
Supply of skills	Being built up including 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

Must fusion follow the same regulatory approach as fission? Lessons are being learned from ITER and in the EU-DEMO dialogue with regulators, but substantiated arguments backed by detailed conceptual designs 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, and this would be greatly assisted by making an early burning-plasma machine sufficiently flexible to allow testing of components whilst also demonstrating operation of a complete set of power-plant relevant technology.The costs that matter will depend on the funders: different emphases are placed on capital, operation, and lifetime costs by different stakeholders. Regarding capital and operational costs it is expected that the largest gains will come from improving manufacturing logistics and reliability, and this may be as important as, for example, a focus on reduced physical size.

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*

The high projected capital cost (and associated risk) of large tokamaks has triggered a range of studies around the world into smaller devices. These compact fusion plant concepts are usually based on technologies or physics regimes that have high uncertainty due to the paucity of underlying data and large extrapolation from existing well-known regimes and technology. In general their integration aspects have not yet been fully examined: the detailed exploration of integration and the needs for operational margin in EU-DEMO has driven the size up. The step to nuclear operation is expected to require many levels of redundancy and safety to be considered and demonstrated with operational data, meaning regimes with limited data may need unconventional approaches to qualification. There are suggestions that there could be cost advantages in combining several small devices on one site, sharing services such as remote maintenance systems and balance of plant (heat exchangers, turbines, power systems, tritium systems, etc.). This needs careful examination as sharing such systems introduces significant complexity and a detailed plant layout and building design is required before such proposals can be consolidated.

III. CONCLUSIONS

Any “next step” nuclear device such as the EU-DEMO 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. This has driven the present approach adopted by EUROfusion [2], although the issues to be solved and the related risks are still significant. This does, however, allow an engineering design approach aimed at identifying integration problems. Alternative concepts, for example those with markedly different maintenance strategies, should be treated with a similar process before conclusions about viability can be reached.

Looking to the transition to commercialization, a prime driver will be cost. It is impossible at this stage, before the demonstration of the wide spectrum of 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.

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 and 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 EU-DEMO programme has shown the importance of examining the integrated design of systems from the outset, and of identifing critical manufacturing steps. Addressing these elements and challenges while aiming for widespread deployment of fusion as early as possible provides a focus for the European programme alongside DEMO.

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