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Author for correspondence:
E. Surrey
e-mail: elizabeth.surrey@ukaea.uk

Engineering challenges for accelerated fusion demonstrators

E. Surrey

Technology Department, UKAEA, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK

ES, 0000-0003-3093-9556

There are several programmes within the fusion community that are engaged in the design of fusion devices to follow the International Thermonuclear Experimental Reactor (ITER), referred to as 'demonstrators'. These programmes have identified many issues over the past decade, and research now concentrates on optimizing the combination of systems against a set of Key Performance Indicators (KPI) which may vary between programmes. While the return on investment in and experience from ITER is seen as an important factor in this research there are significant differences in the operational conditions and KPI of demonstrators that generate additional problems requiring different solutions. Among these problems are the necessary use of uncommon materials for structural and functional purposes, the impact of the availability KPI on basic machine design, configuration and component lifetime and the integration of the tritium fuel and thermodynamic cycles. These raise issues of component manufacture and standards and of resource availability in the required quantities and quality that are independent of device size and design. Interpreting 'accelerating fusion' in a wider sense, the impact of these issues, analysed in respect of developmental timescales, shows that a strategy of early engagement with the industrial supply chain and the development of computational engineering testing and verification will be essential to prevent prolonged timescales to fusion progress.

This article is part of a discussion meeting issue 'Fusion energy using tokamaks: can development be accelerated?'

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1. Introduction and definition of a demonstrator

The design of a fusion device to follow the International Thermonuclear Experimental Reactor (ITER), that will explore the issues relating to a fusion power plant is the subject of several programmes among the ITER participating nations. These devices commonly referred to as 'demonstrators' concentrate on the engineering aspects of fusion (rather than plasma physics), in particular, problems and options relating to the integration of the various systems that will comprise a fusion power plant. Thus, a demonstrator includes systems that will not be developed on ITER, a different set of operational requirements and will produce operating conditions that are far more hostile than encountered in ITER. For example, the cumulative effect of the extended pulse length (or steady-state operation) of a demonstrator over periods of years results in plasma erosion of the plasma-facing material requiring an alternative solution to the beryllium adopted for ITER.

The attributes that a demonstrator device must possess can be categorized as essential and inessential as below.

Essential attributes are:

- all systems relevant to a fusion power plant,
  - (i) thermodynamic conversion to electricity,
  - (ii) closed tritium fuel cycle—tritium breeding blanket, tritium extraction, processing and recovery, tritium storage,
  - (iii) safety and monitoring systems,
  - (iv) heating systems (and non-inductive current drive if appropriate),
  - (v) plasma gas exhaust system and impurity removal,
  - (vi) diagnostics and control actuators,
  - (vii) remote maintenance system, active handling facilities and storage, and
  - (viii) recycling and waste management;
- demonstrate tritium self-sufficiency;
- address issues relating to the economic production of electricity—availability, thermodynamic efficiency, net electric power;
- demonstrate a remote handling scheme that is robust and compatible with power plant requirements;
- demonstrate control of the plasma including mitigation of off-normal events;
- demonstrate safe failure, mitigation of and recovery from fault conditions; and
- licensed by a nuclear authority.

Inessential attributes are:

- generation of electricity at a cost that is economically competitive with contemporary sources;
- demonstration of availability that is of the same magnitude as contemporary industrial standards. These are typically 70–90% [1] but given that availability of existing fusion devices is of order 1%, a value of around 30% represents a more acceptable goal, given the lack of reliability data for most components; and
- demonstration of thermodynamic efficiency that is of the same order as contemporary industrial standards (typically 30–60%). Again, it is difficult to set a specific target as there is no prior experience with a fusion device. Furthermore, the efficiency will be partly determined by the choice of coolant and the operating temperature of the tritium breeding blanket, which is the primary heat source of the thermodynamic cycle. Present demonstrator designs employ water or helium cooling with operating temperature around 500°C. The latter is dependent upon the structural material which for present fusion demonstrator designs is a form of martensitic steel which results in efficiencies at the lower end of the range. Supercritical carbon dioxide has been considered but would

require the development of a different structural material to take advantage of the higher operational temperature.

The essential requirements can be regarded as KPI. Although it is recognized that, by its nature, a demonstrator will not be capable of meeting the economic requirements of a power plant, it is also a condition that it should not rely on any system, operation or methodology that is incompatible with use on a power plant. It follows therefore that the design of components, the choice of materials and manufacturing methods must lead to performance that would satisfy full economic criteria after a suitable period of development.

Various studies of the economic performance of a hypothetical fusion reactor have been carried out, one typical example using the PROCESS code [2] giving the levelized cost of electricity, coe, as a function of time, t, as

$$\mathrm{coe} = \frac{\sum_t (C_t + \mathrm{OM}_t + F_t + R_t + D_t)(1+r)^{-t}}{\sum_t E_t(1+r)^{-t}},$$

where the capital, C, operation and maintenance, OM, fuel, F, replaceable components, R, and decommissioning, D, costs as well as the income stream from electricity sales, E, are discounted back to the start of operation with a discount rate r. The cost of electricity is determined by equating the total discounted costs to the total discounted income stream. For one example, a 10th of a kind 1 $\mathrm{GW_e}$ power plant [3], the coe is dominated by capital costs with the fusion 'core' (magnets, vacuum vessel, fuelling and tritium plant) accounting for 35–40%, while replaceable items such as breeding blankets, divertors and first wall account for an additional 25–30%, and balance of plant approximately 25%. The contribution of operational performance (and decommissioning) is therefore taken to be of order 10% but these relative values are likely to change for smaller plants (both physically and in electrical output) and if more recent analysis of resource cost is used.

No economic studies of a demonstrator exist, but it is likely that the contributions of the core and operations will be proportionately larger given their first of a kind (FOAK) nature while the capital and decommissioning costs will be similar to the power plant model. The acceleration of fusion demonstrators, at least in the short term, is more likely to be achieved by addressing these costs. A parametric study of the operational performance factors contributing to the cost of electricity [4] showed that plant availability was the major single contributor in the operational contribution as shown in the parametric equation:

$$\mathrm{OM} \propto \left(\frac{1}{A^{0.6}\eta^{0.5}{P_{\mathrm{enet}}}^{0.4}}\right),$$

where A is availability, η is the thermodynamic efficiency and P_{enet} is the net electrical output, and A is defined as

$$A = \frac{\sum \text{Mean Time Between Failures}}{\sum \text{Mean Time to Replace or Repair}} + \frac{\text{Time Between Maintenance}}{\text{Maintenance Time}},$$

where the sum is over all relevant systems. Generally, an availability of 30% is considered adequate for a demonstrator and subsequent studies have shown that even this value is challenging.

While availability is largely determined by the remote maintenance scheme, the mean time between failures is determined by the reliability of any given subsystem or component and is thus directly related to the design, manufacture and materials choice. Considering the conditional requirement of compatibility with a power plant, it follows that these three aspects of the engineering of demonstrator components play a significant role in the development programme. It is therefore essential that the assessment of a component design consider:

- design for maintenance—accessible to remote handling in terms of lifting points, fixings, mass, centre of gravity;

- design for manufacture—use of unusual materials without a readily available supply chain, feasibility of manufacture using existing methods, finished product accessible to inspection; and
- testing requirements—availability of testing facilities, testing requirements, number of samples.

2. Factors affecting the design of components

The demands of the fusion environment impose unique challenges on engineers and scientists and influence the choice of materials and the design of components. Additional constraints have been introduced by the fusion community in a desire to avoid the production of large amounts of active waste of long lifetime [4]. This has resulted in a reduced palette of elements considered compatible with materials selection so that design options are compromised. ITER, with its reduced availability, has not been designed as a 'reduced activation' device, so some solutions cannot be directly transferred. For example, for the EU-DEMO, the main structural material for the breeding blanket is EUROFER, a reduced activation ferritic martensitic (RAFM) steel with many of the usual alloying elements replaced [4] whereas ITER uses a specific grade of 316 L, which is non-ferromagnetic.

The demonstrator represents a combination of multiple loads to the designer:

- high heat flux (approx. 1–20 $\mathrm{MW\,m^{-2}}$ normal/$\sim 10^4$–100 $\mathrm{MW\,m^{-2}}$ off-normal) at the plasma facing first wall and divertor;
- irradiation damage—embrittlement, transmutation, swelling—leading to time variation in material properties such as thermal and electrical conductivity, tensile strength, ductility and volume;
- electromagnetic arising from the use of RAFM steel, induced currents from plasma-driven time variations and plasma off-normal events;
- plasma erosion of the plasma-facing first wall; and
- gravity, particularly for large components that will be replaced during maintenance.

As a result, the design of components, especially those that are in-vessel and close to the plasma, such as the first wall, breeding blanket and divertor, requires the use of materials that are not part of the common engineering palette, such as tungsten to resist the plasma erosion, RAFM to reduce waste legacy, and in some cases new materials such as oxide dispersion strengthened (ODS) steel and copper.

The requirement to be self-sufficient in tritium fuel introduces another set of unique challenges as the tritium production process proceeds through the reaction of the fusion neutrons with lithium, another uncommon engineering material (functional rather than structural). The process additionally requires the presence of a neutron multiplier, usually beryllium or lead, as each neutron only produces a single tritium atom and sufficient tritium must be produced to offset losses in the blanket and elsewhere, usually a ratio of T:n greater than 1.1 is desired (the tritium breeding ratio). Thus, the design of the tritium breeder must incorporate lithium and a multiplier containing either beryllium (usually in the form of solid pebbles) or lead (usually as a liquid). This introduces additional complications in terms of material compatibility, corrosion and manufacturing.

The impact of the fusion environment on the design and manufacturing strategy is best illustrated by example. The EU-DEMO designs of two plasma-facing components, the first wall limiter and the divertor, and of two breeding blanket options, are described below as illustrations.

(a) Designing for high heat flux

The two areas where high heat flux is encountered are the first wall protection panels and the divertor plasma-facing tiles. The former are discrete components that protect the majority of the

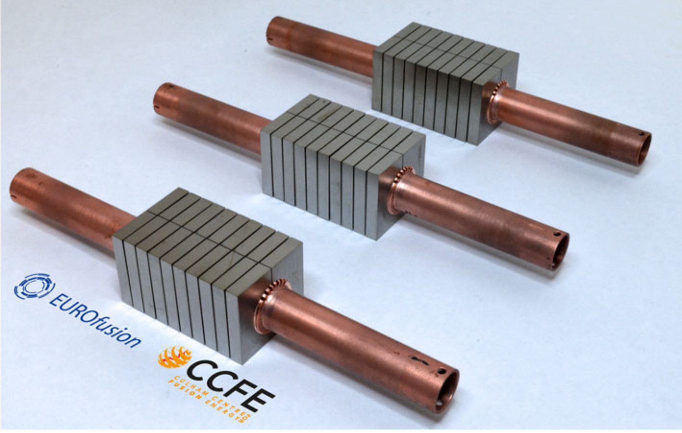

Figure 1. Prototype design of tungsten mono-block divertor elements for EU-DEMO. Shown is the design from CCFE but variants exist from IPP, KIT, CEA and ENEA [8]. (Online version in colour.)

first wall and blanket from fast ion interception and off-normal incidents. They routinely receive approximately 1 MWm^{-2} with up to 20 MWm^{-2} estimated for local effects and off-normal events; irradiation damage rates greater than 10 dpa fpy^{-1} in Cu (displacements per atom per full power year) are expected [5]. The divertor tiles protect the divertor-cooling structure in a region of high heat flux (20 MWm^{-2} routinely [6]) but lower irradiation damage less than 5 dpa fpy^{-1} in Cu [7]. Both components are subject to plasma erosion but this is mitigated in the divertor by the use of a thick (approx. 50 mm) mono-block of tungsten [8], a solution derived from the ITER design and shown in figure 1, but because the ITER first wall is beryllium and has no breeding blanket behind it, its design is not applicable to the first wall protection panels, or indeed any of the first wall structure.

The divertor tiles offer an example of a relatively simple design that potentially introduces quality control issues due to design decisions taken for sound physical reasons. The mono-blocks are mounted on a copper-cooling structure and several designs are under development employing various interlayers between the copper and the tungsten to minimize stress in the former. The mono-block design was adopted to insure against the failure of the tungsten layer; the blocks are fixed to the coolant pipe, so a failed mono-block would remain in place and not expose the cooling structure, unlike a monolithic tile that could crack and flake. The design is also modular for manufacturing convenience but the need to include the interlayer creates a relatively complex manufacturing process with a hidden join that is difficult to inspect. Given that approximately 800 000 mono-blocks will be required in the EU-DEMO divertor, this offers a considerable manufacturing and quality control challenge.

The recent development of ductile tungsten laminate pipes [9] may provide a solution providing the differential thermal expansion between the laminate and the bulk tungsten is not large, although there is evidence that implies the ductility may be lost under irradiation [10].

The first wall protection panels offer an example of the enforced use of unusual materials leading to a potentially complex manufacturing process again with quality control issues. These are also modular in design with a single module shown in figure 2. Figure 2*a* shows a stress map of the design for the base structure of the panel, made from EUROFER, under normal conditions with water cooling at 15 MPa and 280–325°C. A 2 mm thick tungsten armour layer is then joined to the EUROFER to protect it from plasma erosion and figure 2*b* shows the equivalent stress map which shows acceptable values on the surface. Unfortunately, at the material boundary the stress reaches unacceptable levels (figure 2*c*) and will require one or more interface layers between the tungsten and the EUROFER, thus complicating the manufacturing process.

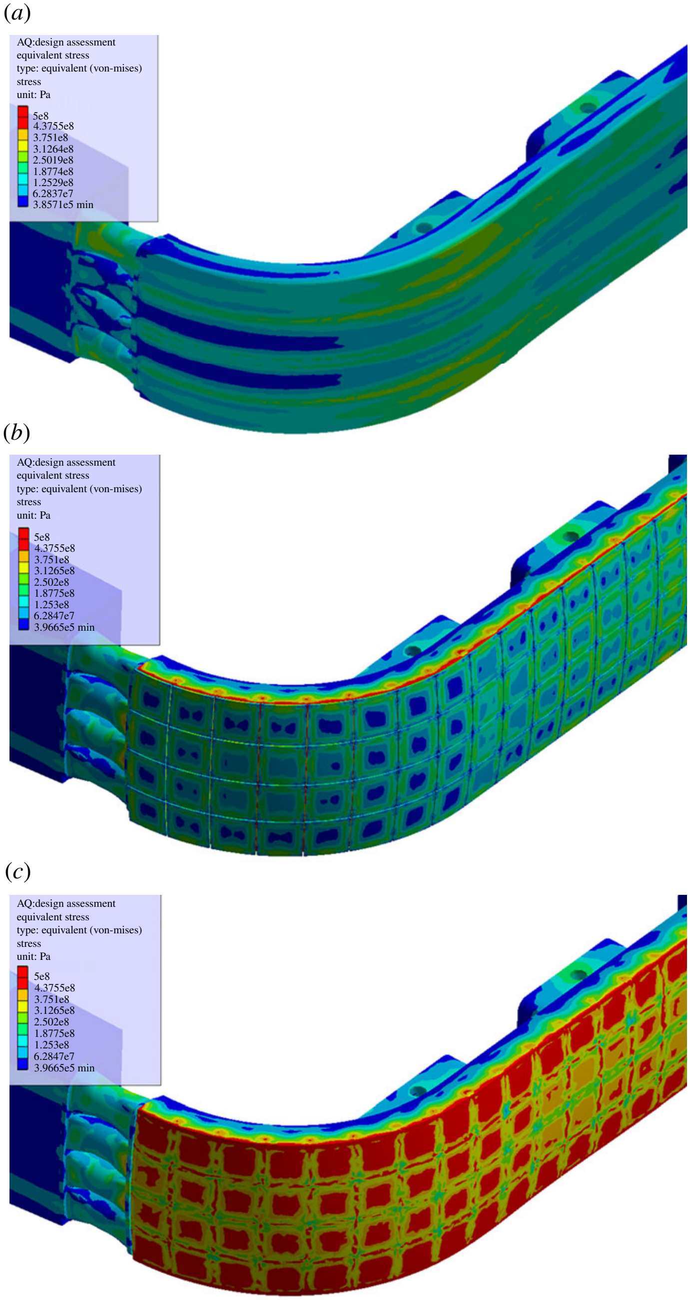

Figure 2. First wall protection panel. (*a*) Stress in EUROFER coolant structure. (*b*) Stress at surface of 2 mm thick tungsten armour layer. (*c*) Stress at EUROFER–tungsten interface.

This is reminiscent of the ITER first wall panel (although with different materials) where the abrupt change in material properties induces excessive stress. Avoiding multiple joins and manufacturing processes is essential to reliability, for example, the ITER-enhanced heat flux first wall panel contains approximately 800 individual welds. For ITER, failure of a panel is inconvenient rather than problematic as it has no availability KPI, unlike a demonstrator.

The adoption of modularity in both the divertor and first wall protection panels for convenience of manufacture introduces additional constraints on manufacture and installation tolerances due to the effect of misalignment on adjacent modules. Gaps between modules and hence exposed edges become inevitable and can increase the received heat flux by an order of magnitude [11]. Some mitigation is possible through shaping of the component surfaces, but this will need knowledge of the probable radial and rotational tolerances of installation and may not be amenable to pre-installation design, particularly given the present uncertainty in the flux distribution from the plasma.

(b) Designing for tritium breeding

The breeding blanket simultaneously performs several functions:

- transfer the fusion power and the nuclear heating arising from exothermic nuclear reactions to the coolant in primary heat transfer system (PHTS) of the thermodynamic cycle;
- ensure Tritium breeding for self-sufficiency Tritium Breeding Ratio > 1.1; and
- shield the vacuum vessel and magnets from neutron irradiation.

The breeding blanket interfaces with many major systems in the demonstrator: its coolant feeds the PHTS of the thermodynamic cycle, it provides tritium to the tritium extraction and purification system, it is intercepted by the heating and current drive, diagnostic and control and fuelling systems. In addition, the blanket structure must be sufficiently robust to allow installation and removal by the remote maintenance system after a period of operation (currently anticipated to be approx. five calendar years in the EU-DEMO with 30% availability, equivalent to approx. 20 dpa irradiation damage for approx. 1 GW fusion power) during which the properties of the structural materials will have changed. *In situ* repair may be impossible, so the initial design must allow high reliability under changing material properties.

The breeding blanket contains the breeding material, lithium, a neutron multiplier, the PHTS coolant, a tritium removal medium and a support structure of RAFM. There are various options and configurations of which two are considered here—the water-cooled lithium lead (WCLL) and the helium-cooled pebble bed (HCPB) blankets, shown in figure 3.

In the WCLL (figure 3*a*), the lithium and lead (multiplier) circulate as a eutectic mixture in the breeder chambers which are cooled by water flowing in double-walled pipes of external diameter 13.5 mm and internal diameter 8 mm with a pipe wall thickness of 1.25 mm [14]. The numerous narrow bore, double-walled tubes that must be connected to a manifold and are immersed in the somewhat corrosive LiPb eutectic represents a complex manufacturing problem. It has the advantage that, in theory, the tritium is extracted with the LiPb (assuming minimum diffusion due to permeation barriers) so no additional extraction medium within the blanket is necessary.

The HCPB is shown in figure 3*b* where a similar complexity of manufacture is evident by the necessity to create narrow galleries containing alternate layers of breeding material, in this case Li_4SiO_4 (15 mm thickness) and multiplier of beryllium pebbles (40 mm thickness) separated by 5 mm thick cooling plates through which the helium gas coolant travels within a 2.5 mm deep channel, again giving a 1.25 mm wall thickness [13]. Note that the tritium breeding ratio is sensitive to the relative distribution of breeder and multiplier over the blanket sector volume of approximately 1 m^3, so the accuracy of manufacture of these structures is important; in this case, e-beam welding is proposed.

This raises another issue relating to manufacture—the use of manufacturing techniques that are not nuclear qualified. This, together with supply chain considerations, is discussed in the next section.

3. Materials, manufacturing and the supply chain

The previous section introduced some of the materials that are now established in the design of fusion components such as tungsten, RAFM and ODS alloys. These materials have little or

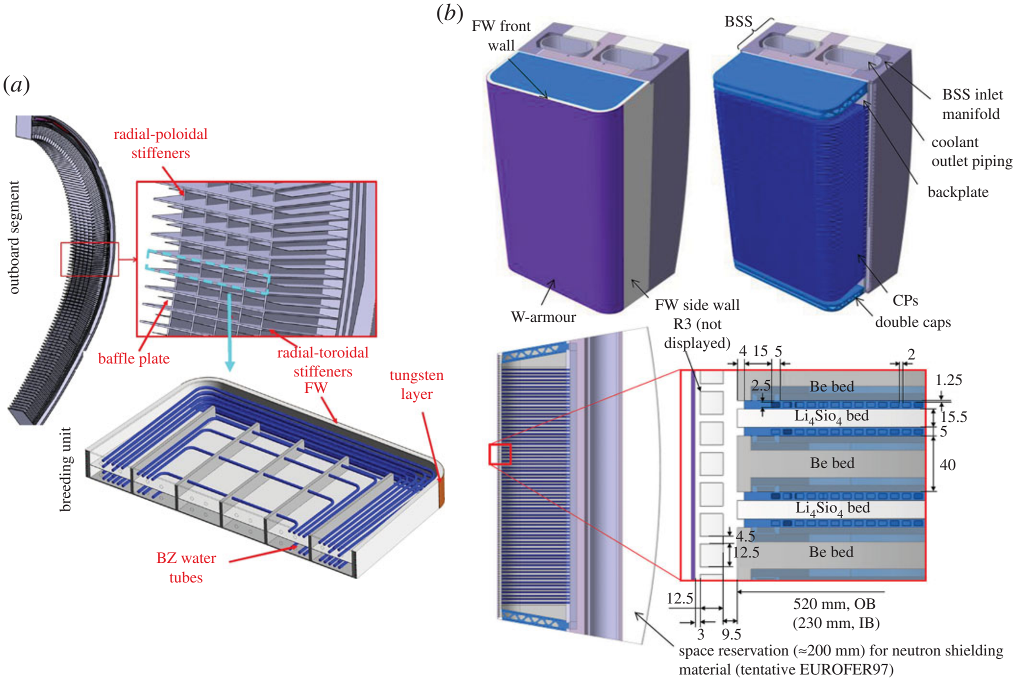

Figure 3. (*a*) Schematic of the WCLL blanket design. The double-walled tubes are shown in blue [12]. (*b*) Schematic of the HCPB blanket design. The breeding and multiplying materials are stored in alternate galleries defined by the blue cooling plates [13].

no provenance of engineering experience; manufacturing and joining methods are relatively undeveloped so designing and prototyping is FOAK in many cases. An additional complication is the lack of design codes and standards for fusion (ITER is using an extension of the French RCMM nuclear code). Existing codes such as ASME [15] and RCC-MRx [16] are based on elastic analysis to derive allowable stress and are aimed at thin-walled, single material constructions so are not suited to the designs being proposed for demonstrator breeding blanket and divertor components [17].

Despite several decades of development, there is no industrial supply chain for RAFM, only intermittent small batch melts have been produced with varying characteristics and properties. Even the tungsten which is readily available industrially has proven to be unsuited to fusion requirements and a specific manufacturing process has been developed.

Many of the structural materials present manufacturing problems. For example, RAFM and ODS steels are difficult to arc weld and, as a result, designers have focused attention on processes such as electron beam and laser welding, explosion bonding, hot isostatic pressing (HIP) and three-dimensional printing, all of which are being increasingly used for non-nuclear applications but are not yet licensed for nuclear applications. It should be noted that HIP offers significant advantages of near net shape production for large items and has attracted interest in the fission community where successful trials of three steels (316 SS, Ni alloy 600 M, low alloy steel) for the manufacture of large items have been trialled [18,19]; unfortunately, none of these steels is relevant to in-vessel components for fusion. ITER has developed HIP as a joining technique for beryllium to CuCrZr, as opposed to near net shape manufacturing, for the first wall panels over the past two decades.

Advanced manufacturing techniques such as HIP, selected laser melting and wire arc have attracted interest in the fusion community for the obvious advantages of production of complex components, but also for their ability to produce graded joints between dissimilar materials. The quality of the materials produced by some of these methods remains variable and is dependent upon the quality of the feedstock. In the case of metal powder, for example, it is essential that powder particle size is controlled within a close specification and that contaminants are excluded, including contaminants that enter via the manufacturing process such as oxygen. Despite the opportunities presented by advanced manufacturing there remains much development work on the materials necessary for fusion applications both in terms of method and supply chain.

The functional materials pose similar supply chain problems, in particular lithium. The cross section for the n,Li reaction that yields tritium is isotope dependent, the ^{7}Li cross section is only significant for neutron energies above approximately 10 MeV, whereas the cross section for ^{6}Li increases as the neutron energy is reduced. The fusion neutrons continuously lose energy as they penetrate the breeding blanket such that only in the first few centimetres is the reaction with ^{7}Li a viable pathway. Thus, most of the breeding material must be composed of ^{6}Li, an isotope that represents approximately 7% of the native metal. Interestingly, ^{6}Li is a by-product of the enrichment of ^{7}Li for use in pressurized water reactor (PWR) fission reactors as a water chemistry control [20] and some demonstrator designs intend to use PWR-type systems due to the ready availability of the thermodynamic cycle plant. Given that significant amounts of lithium will be required (dependent upon the demonstrator design but possibly of the order of tonnes) the absence of a current supply chain on an industrial scale is a major issue, particularly as there seems to be no immediately available industrial process.[1] Similarly, the laboratory scale production of Li_4SiO_4 and Be pebbles currently under development must ensure that the method is scalable to industrial production.

The breeding blankets and fuel cycle components will require tritium permeation barriers to prevent loss into structures and coolants and potentially the environment. These are still under development with some promising results in operation at high temperature, corrosion and hence lifetime [21,22], but limiting tritium transport is a major factor in determining the required tritium breeding ratio of the blanket.

The status of the fusion supply chain is illustrated in figure 4 in which a scale of 1–9 has been used to indicate ‘supply chain readiness’ in a manner analogous to technology readiness levels. In some cases, there are industrially available materials or techniques that are not yet applicable to fusion (such as tungsten and laser welding).

4. Accelerating demonstrator development

To achieve the levels of reliability required to deliver a demonstrator availability of approximately 30% will require average reliabilities over 90% for each system. Obviously, some systems will benefit from the use of industrial standard components, allowing margin for the fusion-specific items. Nevertheless, the complex breeding blanket and divertor structures within the demonstrator will require significant testing during the course of their development to provide reliability data and to identify and eliminate failure modes. Standard engineering techniques such as FMEA have a role to play here but, given that much of the technology will be FOAK, there will be a pressing need to generate a database and this applies to operational issues such as remote maintenance as well as components.

Although the examples used to illustrate some of the problems were taken from the EU-DEMO programme, it should be acknowledged that the general issues exposed—the use of uncommon materials and the manufacturing issues that arise from this, the quality control issues, the development timescales and the need for multiple testing of FOAK components—are not specific to this particular tokamak design. The same issues will arise regardless of device size, configuration or type.

The multiple loads that are inherent in fusion require complex testing facilities. It will not be possible to test large-scale components under nuclear irradiation without building a machine akin to a demonstrator, so it is most probable that the effect of irradiation will have to be included from irradiation of materials in facilities such as IFMIF [23] and the smaller DONES [24] or

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[1] The production of ^{6}Li was undertaken in industrial quantities during the 1960s for nuclear weapons programmes but the process is now only undertaken in China and Russia.

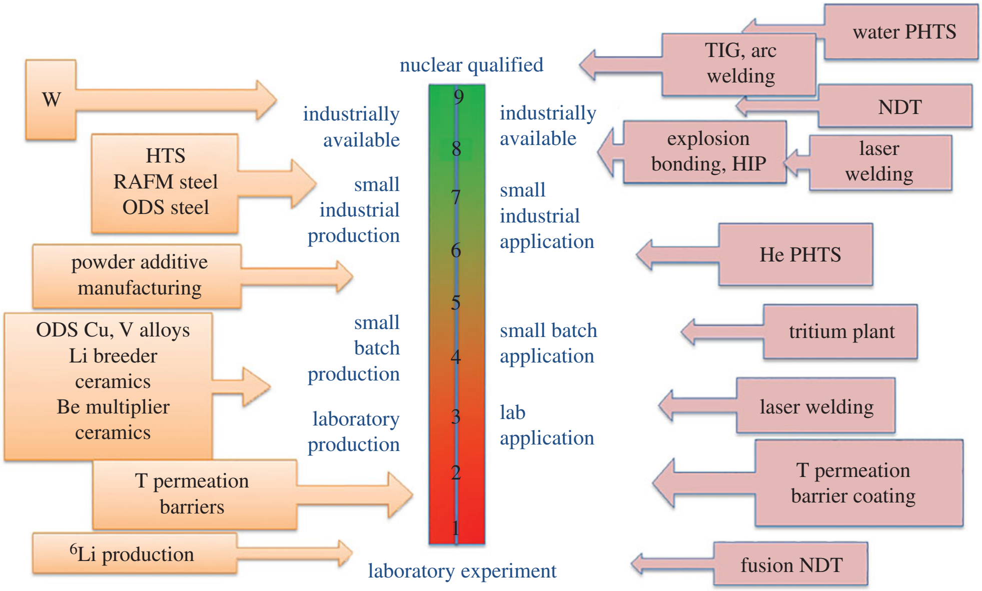

Figure 4. Schematic of industrial supply chain status for materials (left-hand side) and processes (right-hand side). PHTS, primary heat transfer system; NDT, non-destructive testing. (Online version in colour.)

from a combination of fission reactors and spallation sources, although this is less than ideal. Physical testing is time-consuming and expensive—the first wall panels for ITER have been under development for a decade or more and are still only at one-third or one-half scale despite the existence of multiple test facilities. The requirements for the demonstrator are no less complex and will need to include the development of non-destructive testing and monitoring techniques, so development time will be measured in decades unless a different approach is adopted.

Learning patterns show a relative improvement of between 10 and 30% against the nominated KPI per doubling of experience as indicated in figure 5 [25]. Progress is not linear and eventually ceases unless a disruptive element is introduced, such as a different KPI or a new technology. Thus, the demonstrator development can anticipate multiple tests of multiple designs and variations of these designs, not least because failure rates are generally high when FOAK components are involved. ITER has basically tested multiple versions of two designs—a first wall panel and an enhanced heat flux panel—manufactured at a few different facilities.

Physical prototyping and testing is time-consuming, occurring over decade timescales as seen on ITER. It is also detrimental to innovation—the production of physical prototypes requires financial and temporal investment so there is no incentive to explore small design evolutions, the ‘disruptive’ element in the learning process. It is therefore essential that the recent advances in high-performance computing are exploited to develop virtual engineering by multi-field analysis of component design over reasonable timescales. This does not remove the need for physical testing as it is essential that the analysis codes are verified under relevant conditions, but it will allow innovation to be explored quickly and failure to be eliminated without recourse to physical testing. This approach is already being explored in other technological industries such as aerospace and fission which may allow early gains for fusion through collaboration.

This approach is illustrated in figure 6 where the concept has been extended to include whole-plant performance prediction. The continuing need for physical testing to generate data on material and joining performance for novel manufacturing methods will require that physical test facilities are adequately diagnosed, providing sufficient test data to support the models which must be sufficiently detailed. Uncertainty quantification can be used to generate probabilistic failure information for component designs. Combined with information on the

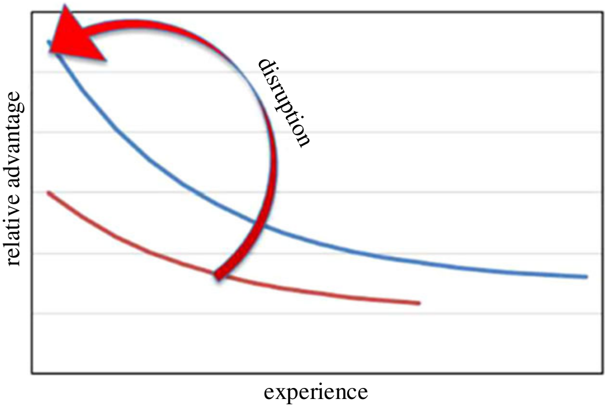

Figure 5. Example learning curves. The development begins on the brown curve and saturates unless a disruptive element (e.g. new design, technology, KPI) is introduced. (Online version in colour.)

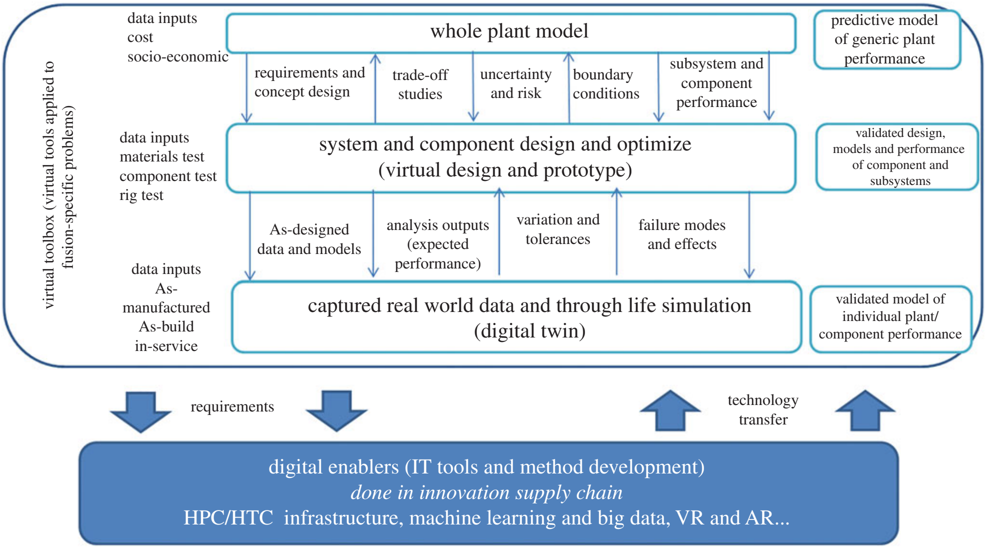

Figure 6. Schematic of virtual engineering implementation for fusion component design. (Online version in colour.)

effects of irradiation on material properties from facilities such as DONES, this will allow life cycle simulations to be performed.

This approach will reduce the timescales for development of the demonstrator components and allow investigation of effects such as nuclear irradiation (assuming an irradiation facility such as DONES is available). It will also allow a wider range of innovative concepts to be explored without the investment in physical prototypes, a major advantage given the likely failure rate that will be encountered for these novel designs and technologies.

It is a truism that developing novel components requires a supply chain of sufficient size and competency—the ability to produce depends upon the presence of competencies and capabilities, both managerial and technical. For business based on emerging technologies, several stages can be identified through which the supply base and customer will pass. These are summarized in table 1 (JD Linton, personal communication).

Fusion spans the top three stages in those areas where existing technologies are not applicable. The ITER first wall and divertor designs sit in Stage 2 but progression to Stage 3 is unlikely

Table 1. Stages of supply chain development for emerging technologies.

stage	description	progress through
1. basic research	no suppliers, unproven technology/ideas, no prototype, no suppliers	products that demonstrate potential value, prototype, initiate/create supply base
2. status of industrial manufacturing	unproven processes, prototype/first generation product, known technology trajectory, limited supply base	products that provide solutions, develop supply base for unique products and materials
3. bottlenecks to development	some manufacturing robust, emerging dominant production processes, initiation of standardization	products easy to manufacture, involve suppliers in manufacturing process
4. stable new technology	robust processes, standardization, supply base approximately 100%	formation of product families, supplier feedback to encourage continuous improvement

given that this technology is not applicable to the demonstrator. (This is not the case for all ITER technology of course.) The demonstrator technology is largely in Stages 1 and 2 and a strategy is needed to progress to the subsequent stages in order to build a supply chain to support the industrialization of fusion.

ITER has been successful in attracting industry to participate in Stage 1 and 2 activities, and it would be wise for the demonstrator programmes to build upon this through early engagement and appropriate partnerships. That this strategy can be successful is shown by the increase in global production of niobium-tin low-temperature superconductor for ITER following that organization's pump-priming of a previously niche industry. More niobium-tin superconducting strand has been produced for ITER than in the entire previous world history.

Given the long timescales involved in present fusion research, there is a danger that expertise and know-how will skip a generation, that learning from ITER will be lost to the demonstrators if their proponents do not engage industry at Stages 1 and 2. This may mean provision within the demonstrator programmes for pump-priming activities in key areas, as undertaken by ITER. Finding synergies with other, established industries should be a consideration, particularly where similar failure mechanisms or conditions are expected.

5. Conclusion

The fusion devices that will follow ITER, commonly known as demonstrators, present a greater challenge to engineering design, manufacture, testing and supply chain than ITER. Consideration of the design requirements and development programmes to meet two of the main challenges for a demonstrator, the high heat flux components and the tritium breeding blanket, have indicated that longer aggregate timescales than those for ITER can be expected, given the added complexity and novelty of the requirements. This novelty will likely require multiple designs and modifications to designs to proceed in parallel in order to achieve components that satisfy the performance demands while reducing the elapsed time. Physical prototyping is unfeasible under these circumstances due to the decade-long timescales and costs and is not conducive to innovation. Developing the virtual engineering capability, possibly in collaboration with other industries, will allow a wider design space to be explored of multiple concepts. This approach will require investment in highly diagnosed, multi-load test facilities for validation of the models which must also be sufficiently detailed. Uncertainty quantification will allow probabilistic failure rates to be investigated along with full lifetime simulation. This approach is not unique to fusion but is being developed in many other industrial areas, so the opportunity to accelerate fusion exists.

In parallel, the fusion industrial supply chain must be developed, building upon the success of ITER. There are certain essential materials, both structural and functional, that have no obvious supply to date. The length of time this may require should not be underestimated and the demonstrator programmes, regardless of device type or size, should evolve strategies to engage with industry to avoid a lost generation between ITER and the next phase of fusion devices.

It should be recognized that the ITER project has already achieved industrial engagement and the demonstrator programmes are an opportunity to capitalize on this to further advance fusion development. It should also be recognized that the international fusion community has progressed from small, experimental plasma physics devices to developing realistic concept designs for fusion reactors in under one decade, less than 20% of the elapsed time since the first tokamak was constructed. The scale of activities required to bring fusion into the industrial landscape may seem daunting, but it is achievable at a national or international scale through well-funded and organized programmes of directed research, such as the EUROfusion programme. These should engage with industry at the earliest opportunity to ensure that designs are compatible with manufacturing capability or to assist in developing capability where it is needed, using and driving innovation in design and manufacturing technology.

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