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# An overview of shared technical challenges for magnetic and inertial fusion power plant development

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Fusion energy is an area of active development and innovation worldwide, with many design concepts studied, each exhibiting a range of technical challenges. A significant portion of technical challenges will be unique for a given design concept; however, there are several overarching challenges that any design must address to some degree. These include tritium handling and the tritium cycle; materials and their survivability in the high-energy neutron environment of D-T fusion; neutronics and the validation of nuclear data; remote handling and maintenance activities; and integrated holistic approaches to fusion plant design. This paper provides an overview of these aspects for magnetic and inertial fusion approaches with a view to highlighting commonality and the benefits of shared knowledge that this may bring.

This article is part of a discussion meeting issue 'Prospects for high gain inertial fusion energy (part 2)'.

## 1. Introduction

Fusion energy has the potential to be a key part of the zero-carbon global energy landscape of the future [1]. Fusion occurs when reactant ions overcome the strong repulsive coulomb force between them and come within a nuclear separation of one another, binding via the strong nuclear force to form new products. For elements lighter than iron, there is a deficit in mass across the reaction which is converted into kinetic energy carried in the reaction products. It is this energy which can be harnessed for electricity production. The need to overcome the coulomb barrier requires sufficient

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kinetic energies of the reactants, and for a high enough reaction rate, this turns out to mean high temperatures in the case of a thermal plasma source. The fusion reaction with the highest cross-section (likelihood of occurrence) at temperatures realistically attainable on Earth is that of deuterium, D, and tritium, T, which has an energy yield from D-T fusion neutrons of around[1] $2.8 \times 10^8\,\mathrm{kJ\,g^{-1}}$; many orders of magnitude higher than fossil fuels. The fuel source for D-T fusion is readily abundant on Earth (noting that tritium will be produced within the reactor itself); however, the technical challenge of fusion is great and needs to be overcome before its formidable potential can be realized.

## 2. Magnetic and inertial fusion

A unifying feature of all approaches to fusion is the need to achieve energy gain; the state in which power production from fusion reactions is greater than the required heating power to sustain the process, or the energy released exceeds to the energy to initiate. The gain factor, $Q$, quantifies this with $Q = 1$ representing the 'breakeven' state where power/energy used for heating the system is balanced by that produced by fusion. $Q$ can be defined for either the plasma or the whole plant (including the efficiency of the heating systems and other energy consumption). A useful parameter for assessing the performance of a thermal fusion plasma towards producing gain is the fusion triple product, which balances plasma self-heating due to fusion against radiative cooling and other energy loss mechanisms. This criterion [2] provides a condition on the plasma density, $n$, temperature, $T$, and energy confinement time, $\tau_E$, by evaluating the balance between fusion energy production and loss mechanisms. Collectively these three parameters are termed the 'fusion triple product' and can be used to provide a simple condition for the state in which plasma self-heating may be sufficient to sustain the reaction:

$$nT\tau_E > 3 \times 10^{21}\,\mathrm{keV\,s\,m^{-3}},$$

for the fusion D-T reaction in the temperature range 10–20 keV. This is true for all approaches to thermal plasma D-T fusion and serves to differentiate them by the way in which this inequality is satisfied.

In *Magnetic Confinement Fusion* (MCF) [2], focus is placed on maximizing the energy confinement time. This is achieved by using strong magnetic fields to confine a plasma in a fixed volume for long times during which heating is applied to achieve fusion conditions. The most mature MCF concept is the tokamak [3] where a helical magnetic field is created in a torus through a combination of externally applied fields, and fields induced by currents driven within the plasma itself. The Joint European Torus (JET) [4] is currently the world's largest tokamak and holds the world record for fusion yield. Despite this record, JET has not and will not reach ignition conditions due to its size. The next stage of tokamak development is represented by ITER [5], a global undertaking under construction in southern France, which will have a plasma volume 10 times that of JET. ITER targets a power gain factor of 10 by generating around 500 MW of fusion power and will be a proving ground for many important technologies. Other magnetic confinement approaches to fusion exist alongside tokamaks at varying degrees of maturity. Notable among them is the stellarator [6] where a helical magnetic field is once again produced in a torus, but in contrast to the tokamak, this is produced entirely via external fields. This brings the advantage of offering true steady-state operation. A tokamak, by contrast, requires the ramping of a voltage in its central solenoid to induce a plasma current, even if it can in principle be sustained indefinitely non-inductively, which necessitates short breaks in operation to reset. The steady-state operation of a Stellarator comes at the cost of engineering complexity.

In *Inertial Confinement Fusion* (ICF) [7], the motion of the plasma is not constrained by magnetic fields (though concepts exist where magnetic fields are key components to ICF also). The confinement time for ICF may have several interpretations, though, for consistency with the fusion triple product, this may be most usefully considered as the ratio of internal power

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[1] https://www.britannica.com/science/nuclear-fusion/Energy-released-in-fusion-reactions.

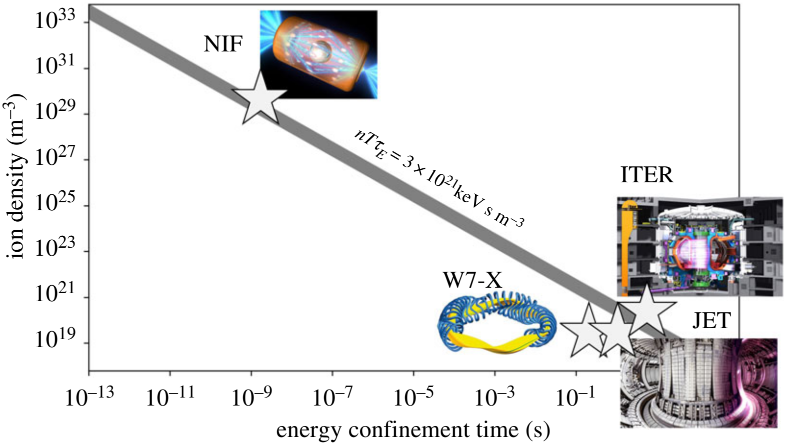

**Figure 1.** Schematic illustration of the difference in approach to energy gain between MCF (JET, ITER, Wendelstein Z-X) and ICF (NIF) concepts. MCF targets long confinement times at lower densities, while ICF targets high densities for short pulses. The greyed area shows the condition $nT\tau_E > 3 \times 10^{21}$ keV s $m^{-3}$ for the temperature range 10–20 keV. While NIF lies above this line, it should be noted that this is with a peak ion temperature of 5 keV which is used to ensure hydrodynamic stability in fuel capsules during implosion. (Online version in colour.)

density balanced against power loss mechanisms, including the explosive expansion of the ICF capsule and/or thermal loss mechanisms in the implosion phase. In this sense, the confinement time may be governed by different mechanisms depending on how the specific ICF scheme is designed; however, in all cases, this is many orders of magnitude lower than in the MCF case. Instead, the approach relies on achieving high densities by driving an implosion of the fuel. This is most commonly induced by high-energy lasers focussed on a small cryogenic fuel capsule, where the ablation of the capsule surface drives an implosion via rocket action. As the fuel implodes, the core is heated to fusion conditions and the high density from compression provides the conditions necessary for burn. Generally, this is aimed at temperatures in the range 5 keV, to avoid hydrodynamic instabilities as the capsule implodes. The National Ignition Facility (NIF) [8] is the largest ICF facility in the world. There is a range of variants of the ICF approach, including indirect [9] (as in NIF) and direct [10] drive where laser energy is coupled directly into the fuel capsule, and designs for next stage facilities such as HiPER exist [11]. The magnetized target fusion (MTF) concept [12], while being inertial in nature, exploits magnetic fields during the implosion process to reduce thermal conduction losses, changing the power balance and reducing the hotspot densities needed.

Figure 1 shows the typical area of parameter space defining the Lawson criterion occupied by the leading MCF and ICF devices (JET and NIF, respectively) and ITER, which is under construction. It assumes $T_i = 14$ keV.

While it is unlikely that fusion will enter the energy landscape much before the latter half of the century, several teams worldwide are designing fusion power plants. Tokamak (MCF)-based concepts are the most mature of these designs with major design programmes underway in Europe [13] (the EU Demonstration reactor—DEMO programme), China [14] (the Chinese Fusion Engineering Test Reactor—CFETR programme), the UK [15] (the Spherical Tokamak for Energy Production—STEP programme), Japan, South Korea, Russia and the US in particular. Major ICF design programmes have also been pursued, most notably the Laser Inertial Fusion Energy (LIFE) Engine [16,17] in the US. In addition, private sector activity in fusion is now rapidly growing with an estimated $1bn of investment to date. Despite the clear differences in approach between ICF and MCF, and the widening of the fusion portfolio, there remains a degree of commonality both in the drivers for the design of power plants, and the technical challenges they face. This is not to say that the commonalities outweigh the differences, nor that at the detailed technological

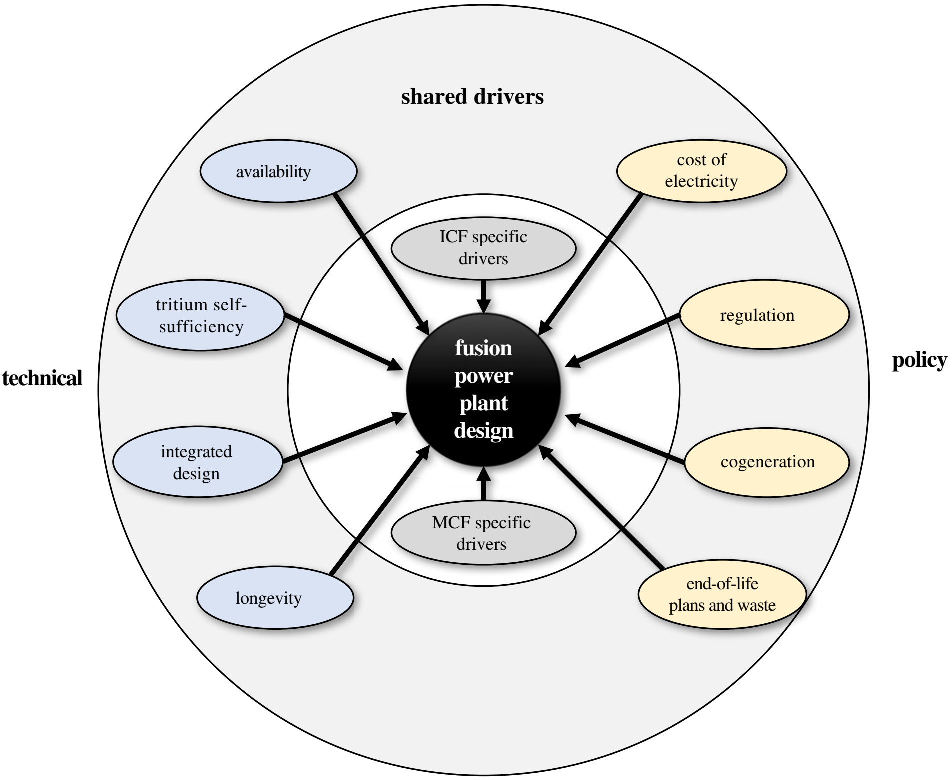

**Figure 2.** Illustration of some common drivers for fusion power plant design. Some of the drivers are technological demands (left-hand side) and some policy requirements. It is likely that the impact on fusion plant design from these common drivers will still differ, but similar high-level considerations still remain. (Online version in colour.)

level there is significant overlap between approaches. Rather this highlights that *despite* the different approaches, there are overarching challenges where commonality may be exploited. The remainder of this paper provides a high-level overview of some of these areas.

## 3. Drivers for plant design

Power plants based on ICF and MCF concepts will clearly differ in engineering design and operation. Due to the need to maximize the energy confinement time, an MCF plant will operate in steady state or long-pulses (greater than 1000 s). By contrast, an ICF power plant will operate in short but rapid pulses (with individual pulse lifetimes potentially less than microseconds) at a frequency optimized to drive a sufficient number of capsule implosions per second to produce gain. Much of the physics basis for the two approaches differs, and some key technologies also vary (magnet technology for MCF compared to laser technology for ICF, for example). Despite the operational differences in the two approaches, power plants based on either method will share a common set of drivers that set the specifics of their design. This is indicated schematically in figure 2 and outlined below.

### (a) Cost of electricity (COE)

The electricity produced by a fusion plant must be acceptably affordable. The abundancy and low cost required to source fuel for fusion reactors (principally deuterium and lithium to breed tritium) mean that the COE is almost dominated by the construction cost of the plant [18]. Naturally, the economic performance of future fusion plants is uncertain given their inherent technological and scientific challenges, and estimates of the levelized COE for fusion plants vary. General expressions for the levelized COE of a fusion plant have been provided by, for example, the PROCESS code [19] which show that dominant contributions are in operations and maintenance, capital, and replacement costs. Principle mechanisms that might vary capital cost are the size of the plant and the modularity of the plant core (i.e. multiple fusion devices to produce higher output), though the capital cost of a fusion reactor is presently hard to predict. Larger plants and/or more plant cores may produce more energy but at increased capital cost. Two major contributors to the operational cost are the availability (§3b) and the overall conversion efficiency of the plant. The efficiency is largely dominated by specific technical details of the core fusion system and is not discussed here; however, availability is impacted by a number of general considerations.

## (b) Availability

Critical to the economic performance of a fusion plant will be the proportionate amount of time spent producing energy, known as the availability of the plant. For current energy supply, this number is typically in the region of 80–90% [20] and fusion power plants must approach if not compete with these levels if they are to effectively penetrate a free energy market in the future. It is controlled mainly by the lifetime of individual components and the time to replace them, but also by unplanned stoppages of the plant core, and the time required to bring the system back online. Unplanned stoppages may include off-normal events in the core fusion system which require shutdown and restart. These events are clearly approach dependant and a short pulse time (in ICF) may be advantageous in that a failed single pulse may have a minimal impact on the net output. Unexpected failure in components of the fusion core, or in external sub-systems of the plant may also cause unplanned stoppages, some of which will be common to all fusion approaches (e.g. the tritium storage and reprocessing plant). In this regard, the reliability of the entire plant must be considered (though component failure in the fusion core remains a key risk).

The high energy density of D-T fusion leads to an inevitably high flux of energetic neutrons incident on machine components and tritium breeding systems. These conditions will result in activation and damage to materials and thereby components which will require a schedule of planned maintenance. To maximize the availability of the plant, this planned maintenance must be carried out as efficiently as possible, and the components must be designed to have as long a life as possible as well as being designed for rapid replacement. The hazardous environment (resulting from activation, the presence of tritium and other hazards), however, requires this maintenance to be conducted without exposure of humans. This necessitates remotely operated maintenance activities.

## (c) Cogeneration

The primary objective of a fusion power plant is likely to be baseload energy supply; however, in many designs, there will be potential for cogeneration. In most approaches to the fusion core, some interaction between high-energy charged particles and materials will produce waste heat (which is a challenge in and of itself, see §3d) potentially producing high temperatures with some components likely to exceed 500°. There is, therefore, potential to harness medium- and (in smaller proportions) high-grade heat presenting interesting opportunities for applications such as utility heating, water desalinization and hydrogen separation. These factors may impact the cost-effectiveness and siting decisions for a fusion power plant, and the degree to which they can be used will depend on device design.

## (d) Longevity

Since the vast majority of the capital cost of a fusion plant occurs during the build phase, it is important that the plant has a lifetime long enough to justify the cost, placing a lifetime requirement on the permanent structures in the plant. ICF and MCF plant designs may differ in which parts are fixed and are consumable (the blanket module in both, the divertor in MCF concepts and the entire first wall in some ICF designs), and therefore, the relative balance between longevity (the lifetime of fixed infrastructure and components in the plant) and availability for components may differ between possible plant designs. Novel materials and efficient maintenance activities are likely to be required to withstand the fusion environment and ensure the plant is able to operate for a sufficient period to depreciate fully the capital costs and offer a sufficiently attractive economic or practical proposition to energy providers.

### (e) Regulatory considerations

Fusion technologies are vastly different from existing power generation technologies and existing regulatory frameworks may not be appropriate for fusion [21] (though it is noteworthy that ITER will operate under an existing nuclear regulatory framework). Plant and systems design will influence the emerging regulatory requirements which will need to be constructed to minimize unnecessary barriers to development while maintaining public confidence through suitable safety measures. Regardless of the core system, several regulatory considerations will be likely to apply to any D-T fusion-based power plant.

A prime regulatory concern will be impact to the local environment. Careful plant design and controlled handling of tritium will be important mitigations to impact on the local environment in worst-case scenarios. The design of the tritium cycle will also determine the total inventory of tritium within the plant which will have implications for licensing—so inventory minimization is a major design driver.

While the fusion reaction products are not active, the presence of high-energy neutrons will cause transmutation in materials of the machine [22], and the presence of tritium will lead to residual tritium embedded in machine components. Accurate prediction of waste and design of waste recycling, detritiation, waste management and decommissioning strategies will likely be regulatory requirements for the licencing of fusion plants.

### (f) Tritium self-sufficiency

Any fusion plant operating on the D-T fuel cycle will necessarily be self-sustaining due to limited global T stock [23]. Fusion plants must breed their tritium. This must be done so with a margin sufficient to compensate: radioactive decay during maintenance periods; tritium temporarily resident in materials and tritium plant which is not available for fuelling the plasma; and for starting up new fusion plants. In addition, the site inventory will be tightly restricted by the regulator, so the amount of tritium outside the plasma at any time must be minimized and losses eliminated wherever possible. This means that very efficient low inventory fuelling systems are needed, the volume of the tritium plant must be minimized, there needs to be fast extraction of tritium from the breeding material and the amount of tritium retained in materials has to be minimized. Self-sustainment will require a form of breeder within the engineering design of the machine which must produce an acceptable ratio of tritium to fusion neutrons to allow for a closed fuel cycle, with surplus to start up subsequent power plants. The design of the breeder and associated tritium plant must be maintainable and must be demonstrably safe with regards to the release of tritium into the environment.

### (g) End-of-life plans and waste handling

The design of the plant does not just affect operational aspects but also the decommissioning processes after the plant has ended its operational life. In addition, it is likely that certain components of the plant will require replacement on a shorter timescale, and the handling of this waste needs consideration also. To process waste (replaced or end-of-life) size reduction will likely be required and due to the active nature of the waste, dismantling will have to be conducted remotely. As with in-life maintenance, a remote approach will favour simpler shapes and a trade-off between bulk and complexity will likely impact the design of the plant. In addition, the choice of material in the machine will impact the replacement rate and decommissioning processes required, and those components which are subject to high neutron fluxes and therefore liable to be activated will need special attention to their materials and design. In general, there will be a need to design the plant with decommissioning in mind from the outset—part of integrated design.

### (h) Integrated design

Finally, all aspects of the plant design must integrate into a single, holistic, functional and efficient plant, and this needs to be considered from the outset [24]. There are many examples of unexpected issues that emerge when integration is attempted. For instance, the first wall armour to protect structural materials from the thermonuclear plasma can reduce the tritium breeding; the blanket operating temperature (thermodynamic efficiency) is constrained by steel properties and the coolant pumping power, and in turn, constrains the fusion power from the plasma; for tokamaks, the recirculating power to sustain the plasma depends on the plasma duration and shorter inductive plasmas may actually increase the overall efficiency compared with steady state.

## 4. Shared technical challenges

Some challenges to realize fusion plants are highly specific, such as the development of high-efficiency, high-power laser systems for ICF [25] or developing an effective heat exhaust solution in MCF [26]. Regardless of the core fusion system though, there are a number of common high-level drivers to all fusion power plant designs, and it is, therefore, natural that a set of shared technical challenges should emerge. The detailed technical design will almost certainly differ between all fusion plant designs, but the overarching motivating challenges remain and may provide fertile opportunity for knowledge transfer and collaboration between plant designs.

### (a) Tritium cycle

Tritium is a scarce resource [23] and, due to its radioactivity, is difficult to operate with. There are extremely limited supplies of tritium available on the planet, the majority being produced from heavy-water fission reactors such as the Canadian CANDU reactor design (now deployed outside Canada). There are strong technical, political and economic motivations to limit the commercial production of tritium to levels not vastly greater than those of today, so fusion plants of the future will need to be mostly or entirely tritium self-sufficient for operations. Excepting the potential for a small start-up requirement, tritium in a fusion plant will be produced, processed and recycled into the fusion core in a closed loop. This cycle is illustrated schematically in figure 3.

In order to achieve a closed fuel cycle, the 'tritium breeding ratio' (TBR) must exceed unity. TBR is defined as

$$\mathrm{TBR} = \frac{T\ \mathrm{bred}}{T\ \mathrm{burnt}}.$$

The design of the $T$ breeder is vital to achieving $\mathrm{TBR} > 1$. The best candidate reactions to produce $T$ are between the D-T neutron from the fusion reaction and lithium, either as Li-6 or (the more commonly occurring) Li-7 [27]. Breeder candidate materials exist as liquids (favoured by ICF schemes without the added complexity of magnetic fields) or as solids, both likely requiring neutron multipliers to increase the number of neutrons for breeding. In general, breeders for fusion plants are at a low technological readiness level; no breeder blanket has ever been built or tested. However, much design effort has been devoted to breeder blankets, particularly for the EU DEMO MCF reactor concept [28]. Many aspects of the fusion core can constrain the blanket design, generally more so for MCF than ICF. In addition, the choice of liquid or solid

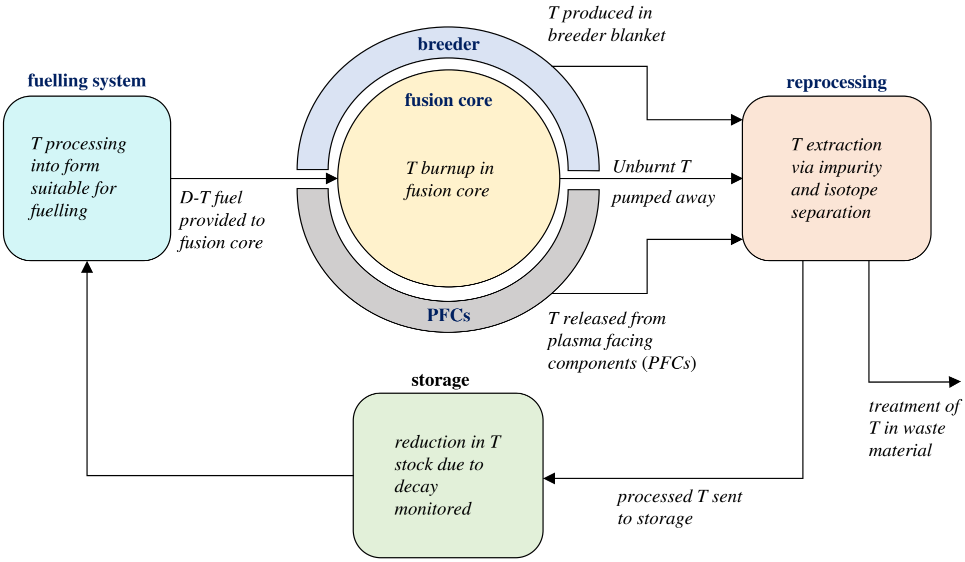

**Figure 3.** Schematic illustration of a typical tritium cycle for a fusion power plant. Specific details at each stage will vary, but the baseline requirements will remain. (Online version in colour.)

breeder material and the choice of coolant/heat transfer medium need to be carefully considered. ITER will provide an invaluable testing opportunity for breeders, with the Test Blanket Modules (TBMs) [29] providing testing of four tritium breeding systems with either water or helium coolants. In addition, tritium plant designs (which are generally much more complex than the simple schematic in figure 3) may be optimized to increase the TBR—a 'Direct Internal Recycling' system is currently envisaged for the EU DEMO design to improve breeding efficiency, for example [30].

The burnup fraction of tritium (percentage of tritium within the cycle used up in the fusion process) is highly dependent on the specific approach to the fusion core, although may not be strongly impactful under variation in a particular fusion core design. The rest of the cycle, however, remains reasonably agnostic to the fusion core. There will broadly be three sources of tritium exiting the fusion core: tritium not burnt in the fusion process will be exhausted from the fusion core; tritium produced in the breeder material must be transported out of the blanket, either embedded in the liquid flow for a liquid breeder, or outgassed from porous solid material; and a standing inventory of tritium embedded in plasma-facing surfaces. These supplies of tritium are passed to a processing plant (though in some designs, a portion may be directly recirculated into fuelling systems [30]) where hydrogenic isotopes are recovered and are then separated and sent to storage such that the D-T fuel mix can be processed into a form suitable for entering back into the fuelling systems to be sent back into the fusion core. The detailed processing requirements between different fusion approaches will certainly vary; in ICF, cryogenic fuel capsules must be fabricated within the tritium cycle, while in MCF, it may be possible to bypass a significant portion of the processing by direct re-circulation of the exhaust gas mix. The successful operation of the JET Active Gas Handling System (AGHS) [31] during the DTE1 fusion campaign in the 1990s demonstrated successful operation of a tritium processing plant over 3 years of operation, providing an existing basis of experience. However, the inventory of tritium required for future fusion power plants will be orders of magnitude higher than that of JET (many kilograms compared to grams in JET). Depending on the breeder design, coolant requirements and design of plasma-facing surfaces, tritium may enter the tritium plant through a number of means including in a He purge gas line, in a coolant line or transported within a liquid breeder. Several processes exist to separate and isolate tritium but novel development is required to improve efficiency. One key area that may play a critical role in the future is the area of tritium permeable membranes; materials (usually specially manufactured metallic or ceramic) able to effectively allow permeation of tritium in isolation from other hydrogen isotopes or elements. An example of the deployment of such materials is in the Permeation Against Vacuum [32] concept where a tritium containing liquid flows against one side of a permeable metallic membrane. Tritium permeating through this membrane is then pumped away and recovered. Tritium permeation and tritium permeable membranes are an active area of development likely to influence the design of tritium plants in the future.

On the other hand, tritium, being an isotope of hydrogen, can readily permeate through metals (particularly when heated) which means that, if left unmitigated, it can migrate around the plant. This is particularly true in the breeder blanket, where tritium may diffuse into coolant loops, and then via permeation through steel pipework, into the local atmosphere. Measures to avoid tritium release will be an important operating feature of a plant, which also help to minimize the loss of tritium from the cycle and therefore minimize the required inventory of tritium. Regular recycling of the local atmosphere via the tritium reprocessing plant (for example, the JET Exhaust Detritiation System also recycles the local operational atmosphere alongside purge gas from the machine) can both help to purify the atmosphere and maximize the recovery of tritium. A key development that will assist in the prevention of tritium migration are materials that can act as permeation barriers. Such materials will be coated or bonded to pipe work and vessels in areas of the plant where tritium release is a concern. A major challenge to this approach is the formation of continuous coatings on the surfaces required. Both oxide- and non-oxide-based ceramic coatings have been developed, with oxides such as aluminide-based coatings offering potential routes towards effective permeation barriers [33]. The properties of permeation barriers should remain effective after neutron irradiation for a sufficient period before replacement, and development of these materials towards radiation hardness will be important for the design of future fusion plants.

## (b) Materials

Availability and longevity are critical for an economically viable fusion plant and the choice of materials has strong bearing here. Materials in different parts of the plant may have to endure extreme fluxes of heat, energetic particles, deuterium and/or tritium, and high-energy neutrons. This can cause melting damage, erosion and sputtering, tritium or deuterium embedding to deform material surfaces, and intrinsic damage from neutron irradiation. Depending on the approach and design of the fusion core, materials may have to tolerate high magnetic fields, creep and cyclic fatigue, and the potential for high-power laser interaction which may impact specific materials choices in some parts of the plant. Nevertheless, the survivability of materials in these environments is required for fusion power plant designs to be cost-effective.

The neutron flux from a fusion reactor may be as high as in the range of $10^{18} - 10^{20}\,\mathrm{n\,m^{-2}\,s^{-1}}$ which can cause significant materials damage on the order of 10 s of displacements per atom (dpa) for exposure of a small number of years. Understanding the damage and changes in material properties caused by neutron irradiation is important as material candidates for fusion reactors must be able to withstand irradiation at this level for up to years at a time. In addition, the choice of material to be used will necessarily be selected well before the plant comes online. To assess the suitability of materials at a macroscopic level in the machine, a deep fundamental understanding of the behaviour of materials after damage via neutron irradiation is required. This is a complex and multiscale problem where physics on the atomistic scale can impact mesoscale features, presenting a challenge in modelling. In practice, some form of scale separation is often required, with modelling treatments differing on different scales. Atomistic models are capable of modelling the formation of dislocations, for example. Dynamical models of dislocation behaviour [34], derived from the atomistic scale models, can then be used to model the interaction of dislocations and multi-dislocation dynamics. These can then feed further up the chain until a representative mesoscale then macroscale model for the material exists. Combining multiple modelling techniques at multiple scales and for several materials and their joints to model a full component or even a subcomponent in a fusion reactor design is a formidable challenge, probably calling for innovative techniques as well as exascale computers, but is an important step towards fully predicting and thereby optimizing the performance of future machines. Major steps on this path have been accomplished in recent years, for example, in ref. [35].

Much materials testing can be performed in experimental nuclear test reactors (MTRs) at present, although neutron spectra in these experiments are not fully representative of D-T fusion, much of the structure sees the 14 MeV fusion neutrons heavily moderated so fission-spectra are a good approximation for many of the processes, and some other effects, such as helium production by higher energy neutrons, can be simulated by implanted atoms that generate helium at lower energies. However, the gap does need to be filled, especially for the regions close to the interior surfaces, and neutron sources with well known, well-calibrated spectra representative of the D-T fusion neutrons are required. This can be done with either a D-T source or a beam-driven stripping reaction tuned to have a similar spectrum and very high flux, significantly above that expected in a fusion plant allowing accelerated testing, and this is the focus of the main effort at present, DONES [36]. DONES (DEMO Oriented NEutron Source, planned in Spain) is an ambitious international programme underway as part of the larger IFMIF (International Fusion Materials Irradiation Facility) project to address the shortfall in D-T neutron flux for materials qualification. In the intermediate period before the full-scale DONES facility becomes operational, an increase in the number and availability of current facilities will provide a valuable step for quantifying nuclear cross-sections and down-sampling tritium breeder material choices in preparation for fuller qualification on DONES. For scientific research, at present accelerator-based neutron generators, such as the Frascati Neutron Generator (FNG) [37] and the Japanese FNS facility [38], for example, can produce D-T neutron fluxes in the range of $10^{11} - 10^{14}\,\mathrm{n\,s^{-1}}$. At these levels, materials damage testing is challenging; however, applications for the measurement of reaction cross-sections for nuclear inventory validation, shielding and some initial breeder testing are within scope. Facilities based on these technologies, or alternatives such as the Gas Dynamic Trap [37] producing similar output, are few in number at present. The full pathway towards qualification of materials for fusion plants will require careful experimentation in high neutron flux environments coupled with multiscale simulations and theory-based modelling.

Experimentation and testing of materials is an important aspect of the selection of materials for a reactor. With many material concepts and components for fusion reactors being bespoke it is important to maximize the efficiency with which testing can occur. Advances in testing techniques have greatly expanded the capability to test materials and components. One such advance has been in the field of micromechanical testing; measurements of material properties on specimens with small (<mm) samples sizes. This has the great advantage that several tests can be carried out using single specimens which allows for a drastically increased number (or rapidity) of tests, and in particular allows irradiated (and hence active) materials to be tested with much simpler safety systems due to the greatly reduced hazards, e.g. in universities rather than bespoke ‘nuclear’ facilities. In addition to novel micromechanical testing, new and modified ion (rather than neutron) irradiation methods offer the ability to cover a wider range of irradiation parameters, improving the range of testing available. One particular method, described in ref. [39], uses a heat source and sink attached to test samples to induce a thermal gradient across the sample. Ion irradiation of these samples now provides multiple data points at different temperatures during a single irradiation, in orders of magnitude less time than for neutron irradiation, although the (substantial) differences between ion and neutron irradiation have to be understood before they can be used reliably.

### (c) Neutronics and radiation transport modelling

Neutrons play a fundamental role in determining many aspects of a fusion plant’s design. The choice of tritium breeder material and design is influenced by the expected neutron fluence into the breeder and its energy spectrum throughout it (which may differ for different approaches to fusion). The level of operational and end-of-life waste depends on neutron interactions with different machine components and the transmutation chains that may occur subsequently. Again, the neutron flux and energy spectrum has to be known accurately throughout the component's volume. Another important aspect of fusion plants is the shutdown dose rate and operator dose rates in remote areas. The dose rate (mainly $\gamma$-rays) in and around the machine is an important part of the remote maintenance strategy since electronics and indeed the actuators are affected by the radiation environment, in turn affecting equipment choices, development needs and the maintenance approaches. Simulations using nuclear frameworks such as FISPACT-II [40] act as tools accessing nuclear data libraries to predict these effects, optimize the designs to minimize waste and will be vital in helping to design the maintenance schedules of future reactors. These simulations will also provide information to regulators during the planning phase and quantifying radiological waste levels allowing for planning of disposal during decommissioning activities. Modelling tools require comprehensive data libraries of nuclear cross-sections to account for many possible reactions. D-T fusion produces neutron spectra peaked at 14.1 MeV; however, the difficulty of producing D-T neutrons in large quantities make it challenging to produce sufficient data for interactions with different materials in the machine to achieve the required accuracy.

From the simulation side, the relative sparsity of nuclear cross-section data can lead to uncertainty in code outputs. As the codebase matures and simulation outputs become increasingly complex uncertainty quantification and, in particular, quantification of error propagation will become important features for the production of ever more robust predictions in the absence of improved nuclear cross-section data. Likewise, validation and verification play an important role in establishing the fidelity of code predictions. Tools for validation and verification of inventory codes [41] and, importantly, multiple nuclear data libraries are now reaching a mature level where rapid testing of libraries can occur, providing feedback to developers for improvement. Nuclear inventory calculations and neutronics simulations continue to provide valuable and vital input to fusion plant design. The challenge ahead is to complement these code-based efforts with an increased capacity and capability for experimental testing and quantification to improve the reliability of simulations.

### (d) Remote handling

Whether for planned or unplanned shutdowns, plant assembly or regular maintenance tasks during operation, the environment within which these operations will occur will be strongly active, presenting high radiation levels preventing human access. This necessitates an approach to the maintenance of the plant which does not require human intervention: remote maintenance [42]. Maintenance may cover a range of large-scale activities such as replacement of a major piece of the plant, of smaller scale regular activity such as inspection (and servicing when required) of welds. In addition, the majority of decommissioning activities will need to be conducted in a similar manner for the same reasons.

In both ICF and MCF approaches, there is the potential for large components weighing tens of tonnes. Whether for maintenance or end-of-life activities, complex loads of this order of magnitude will need to be disassembled, lifted and manoeuvred. A clear example from ICF is the wholesale replacement of the target chamber and the surrounding blanket. Similarly, replacement of blanket modules or divertor components in MCF concepts will require manipulation of heavy components. There will be a requirement for precision when operating on large equipment of this nature which, in turn, places a requirement for high tolerances in the remote maintenance systems. This becomes more challenging as the size and scale of the components grow. In addition, there is a cost of space when handling heavy components; there must be enough space to manoeuvre and coordinate all activities and operations required to remove and maintain the equipment. These operations must also be carried out while remaining seismically stable. This drives plant design towards smaller, lighter individual components and higher levels of granularity in the decomposition of the plant for maintenance/decommissioning. However, granularity drives complexity; a higher level of decomposition of the plant requires more connections and joints which will require inspection and servicing from both a maintenance and regulatory point of view. It is likely that many of these service connections will be in difficult to reach locations and/or within sensitive parts of the plant. This, therefore, highlights difficulties associated with access to hard-to-reach locations and safe (with respect to the operation of the plant) conduct of activities.

Many maintenance tasks would be challenging in their own right; however, the requirement for tasks to be carried out with no direct human interaction brings additional complexity and technical issues to resolve. All tasks are carried out within the exclusion zone of the plant. There are a range of such tasks and the complexity of the plant will lead to a large number of tasks requiring completion with sufficient regularity to satisfy both maintenance and regulatory requirements. As a result speed and parallelization of maintenance tasks will be important factors in remote maintenance operations. Innovation will be necessary to make routine tasks autonomous, providing much faster systems of maintenance. One option could require intelligent control systems capable of managing a connected autonomous fleet of robots such that a single operator may be able to oversee many operations, reducing the (likely high) resourcing requirement for maintenance and/or decommissioning activities. Since the availability of the plant will be crucial, robustness will be an important aspect of maintenance. Such automation of activities must be mature to an extent that intelligent decisions can be taken while monitoring plant conditions. This will allow for a predictive approach to maintenance increasing robustness and availability. In addition to driving up the complexity of the maintenance tasks, the highly active environment means that the robotic technology used for the tasks must be resilient to radiation damage, ensuring that schemes of maintenance are able to operate despite the high radiation environment.

Development of these technologies is a key challenge for fusion power plant deployment and a significant international effort is ongoing in response. An important aspect of this technological development is scale mock-up testing of solutions *in situ* allowing for the important step of verification and validation. As an example, the remote handling system on JET is a tele-operational system using human-in-the-loop operation. Two force reflecting manipulators are supported on 10 m articulated booms and controlled remotely using haptic controls. The JET remote maintenance system highlights the value of V&V. All remote maintenance operations on JET are rigorously specified and tested; the task sequencing is first designed in a virtual environment before testing in a scale mock-up environment. The value of this approach is reflected in many successful remote handling operation campaigns on JET (for example, the full refit of the inner wall to begin the ITER-Like Wall phase of JET operation). It is well suited to pre-defined operations but has also been used to handle unexpected discoveries, in this case making use of cameras (which may be harder in a harsher radiation environment) and the person in the loop as a precursor to autonomy.

## (e) Integrated design

Several key technologies (among a wider technological field) that must be developed for successful fusion power plant design have been discussed in the preceding sections. However, the complexities of fusion plant design drive a need for an integrated design approach. For example, the breeder blanket must maximize the TBR of the plant, operate at a temperature that allows high thermodynamic efficient but is within the operating range of the steels used to construct it and also be maintainable. During maintenance, the blanket structures may retain activation heat which must be accounted for in maintenance procedures. Novel materials are likely to be required to minimize waste; however, joining to such materials is often challenging and requires novel techniques and testing. All of these challenges must be integrable with the demands of the fusion core, and therefore, a holistic approach to plant design from the outset is required for a successful fusion reactor. The high capital cost to develop prototypes for many of the solutions to technical challenges for fusion make a design program via multiple prototypes unfavourable. Instead, an integrated digital engineering framework [24] may offer the ability to rapidly test solutions via simulation however significant development will be required to achieve this. Such a framework cannot fully qualify a solution, which requires physical testing, but using these two methodologies in conjunction may provide a more optimized pathway towards qualification. Furthermore, a digital framework offers an approach to develop and down-select solutions in an integrated holistic manner, reducing the required design time and focusing technological development towards fewer favourable solutions. It is worthwhile noting though that the development of such a framework is a technical challenge within itself and will require dedicated expertise but will be a valuable step on the road to designing fusion plants. This is an area being explored in many fields and industries, bringing scope for strong mutual synergies between fusion and the wider research and industry communities.

## 5. Summary

Fusion energy has the potential to be a key part of the zero-carbon global energy landscape of the future. There are many approaches under development worldwide which are broadly categorized as either ICF or MCF fusion. The details vary greatly, and each approach has a set of unique and technically demanding challenges that need to be addressed in the push towards realizing fusion. Nevertheless, there also exist a subset of common overarching challenges providing an opportunity for knowledge transfer and expertise sharing between different approaches to fusion. These include tritium handling and the tritium cycle; materials and their survivability in the high-energy neutron environment of D-T fusion; neutronics and the validation of nuclear data; remote handling and maintenance activities; and integrated holistic approaches to fusion plant design. All of these challenge areas are key activities within the fusion community and require continued technical innovation and development to realize fusion energy production.

Data accessibility. This article has no additional data.

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