ITER and DEMO – Technology Challenges on the Way to Fusion Power

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Introduction

Nuclear fusion promises virtually unlimited energy production in a sustainable manner with a reduced radiological risk due to the absence of a nuclear power escalation. However, the technology is complex and still in the stage of step-wise maturation. While recently, remarkable progress has been achieved at the US Lawrence Livermore National Laboratory with a laser-driven, inertial fusion approach, the fusion development in Europe mainly focuses on magnetic confinement fusion, where a solid plasma physics basis beyond the actual implementation of the fusion reaction itself has been established. The international experimental fusion reactor ITER, currently under construction at Cadarache in the South of France, as illustrated in **Figures 1–2**, and the design of a Demonstration reactor (DEMO) within the EUROfusion project are the cornerstones of the European development. Nuclear fusion requires challenging solutions in quite a number of technological and technology-related areas. Game-changing solutions are being targeted by start-up companies aiming at early deployment of fusion; still, even if successful, these will not resolve all the challenges/requirements at once, and will not make obsolete the need for integration of the remaining subsystems and for licensing. This article provides a brief overview on the technology and related challenges on the way to magnetic fusion energy.

Fig. 1
ITER construction at Cadarache, France: Aerial view of construction site.
(Credit :© ITER Organization, http://www.iter.org/)

ITER

ITER shall, for first time, demonstrate a magnetically confined, self-heating (i.e. "burning") plasma on the basis of the D-T fusion reaction:

$$\mathbf{D + T \rightarrow He + n + 17.6\ MeV}$$

According to momentum conservation, 80 % of the reaction energy (i.e., 14.1 MeV) is carried by the neutron leaving the plasma chamber domain, while the remaining 20 % carried by the He ion is "captured" within the magnetic confinement of the plasma domain and provides heating of the plasma fuel through collisions, thus allowing to maintain the fusion reaction. The goal of ITER is to reach a Q factor of 10, i.e., to produce 10 times more fusion power than power injected into the plasma by the heating systems. This simple consideration, however, does not take into account the efficiency of the heating systems, i.e. that the power effectively injected into the plasma is lower than the power supplied to the heating systems. E.g., for the Electron Cyclotron Resonance Heating (ECRH), an efficiency (or conversion factor) of 50 % appears to be in reach. Similar arguments for the efficiency hold for a set of electrically driven technical systems required to operate a fusion reactor, such as magnet system, cryoplant, fuel cycle. Furthermore, the thermodynamic efficiency providing the electric power by extracting heat from the blanket for conversion, i.e. in turbine, is well below unity.

ITER will be the central facility to demonstrate a self-sustaining "burning" plasma through α-particle (He ion) heating. So far, Q factors of ~ 0.7 have been achieved with D-T reactions in the Joint European Torus (JET), a facility in operation since almost 40 years now. JET, however, is constrained to a low magnetic field produced by normal conducting magnets, and its fusion power is by its small size. The point in time when the "burning plasma" will be reached in ITER is currently subject to a re-baselining caused essentially by non-conformities of delivered components. According to the previous schedule, fusion plasma operation has been foreseen in the early 2030ies. While ITER remains crucial for the European Roadmap to fusion power, the behaviour of the "burning plasma" can to a large extent be anticipated by more and more sophisticated modelling approaches used to define the successor of ITER, DEMO, as discussed below. So, while no surprises are expected, validation and eventually correction of the models is indispensable before the design of DEMO can be finalized.

Fig. 2
Assembly preparation of toroidal field coils.
(Credit :© ITER Organization, http://www.iter.org/)

ITER is based on a tokamak, i.e., the fusion plasma is confined by strong magnetic fields forming a torus shape. It will rely on a number of technological systems, part of which have been validated on JET and other plasma physics experiments worldwide; nevertheless, due to the challenges of the large scale of ITER, most of these will be "first of a kind". To be mentioned here are the magnets confining the plasma, the plasma heating systems also providing current drive necessary to maintain the plasma, systems for plasma diagnostics and control as well as for power and particle exhaust. Given the radiotoxicity of tritium, a closed deuterium-tritium fuel cycle is required. ITER will also be used to determine Beginning-of-Life effects in modules, called blankets, for testing the self-production of tritium. As the D-T reaction will produce neutrons and hence activation, remote handling systems will be required. An overarching challenge of course is safety demonstration and licensing.

DEMO and the European Roadmap

Different from ITER, DEMO shall demonstrate electricity generation out of fusion power – in a way that commercial attractiveness comes into reach and industrial actors will take over. It is thus the central element of the European Roadmap to Fusion Energy **(Figure 3)**.

As much as possible, DEMO will rely on technologies already developed for, and validated with, ITER. Nevertheless, a number of new technological challenges has to be mastered. First and above all, DEMO will accumulate substantial doses of neutron exposure and damage in the components located within the vacuum vessel surrounding the plasma. Thus, DEMO requires neutron-resistant materials in order to achieve a reasonably high duty cycle and overall time of operation, which is one to two orders of magnitude above the overall neutron wall loads calculated for ITER. While for ITER, the expected damage and activation level in the structure does not require specific pre-cautions and allows using materials certified in nuclear power reactors, DEMO has to anticipate commercial power plant operation requirements, specifically with respect to materials and component lifetime simultaneously at a low activation level, which requires dedicated low activation neutron-resistant materials, being different from those of nuclear fission reactors. The qualification of these materials in a fusion reactor typical neutron spectrum is indicated by the line "Material research facilities IFMIF-DONES" in the Roadmap sketch, as shown in **Figure 3**.

While the tritium for the operation of ITER will be supplied externally, DEMO will have to produce its own tritium after the initial filling – also in line with the requirements for a fusion power plant. This entails the deployment of a new fuel cycle technology and the related systems, i.e., the tritium breeding blanket inside the vacuum vessel. While test blanket modules will be inserted in ITER without direct impact on ITER operation, a reliable operation of the tritium breeding blanket will be a pre-requisite for operating DEMO as a whole. Furthermore, suitable remote-maintenance technologies have to be developed for the regular exchange of this component, capable to operate reliably at high shut-down dose rates. The closed DT fuel cycle of ITER cannot be extrapolated to DEMO, as the tritium throughput will be by orders of magnitude larger, which is a consequence of the higher duty cycle and the higher overall thermal power (1–2 GW of DEMO vs. 500MW of ITER). Since the tritium release to the ambient is restricted to quite low quantities and also the tritium amount in components is limited for licensing reasons, the DT-fuel cycle is targeting to minimize the overall tritium inventory, thus requiring new solutions be developed.

Electricity generation in a DEMO-reactor cannot be directly copied from existing nuclear fission power plants due to the inevitably pulsed operation of a tokamak reactor. Here, advanced energy conversion technologies based upon helium at high temperatures and the use of thermal storage technologies are under development to decouple thermal power generation from power conversion as addressed in the section Balance of Plant. Last but not least, the ongoing experience of ITER licensing has shown that it may not be the best solution to apply the existing standards and procedures developed for nuclear power plants. A new approach for fusion power plant licensing will have to be developed which is based on the hazard potential of the systems and components and is currently under discussion within the IAEA.

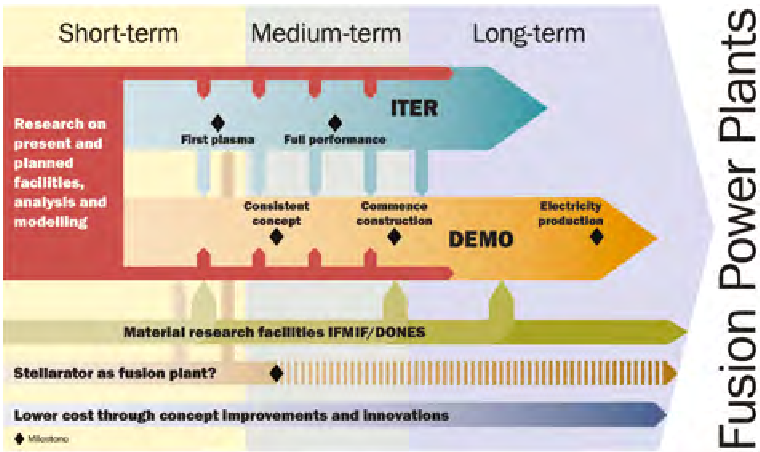

Fig. 3
Schematic representation of the European Roadmap to Fusion Energy.
(Figure taken from: A.J.H Donné et al., "European Research Roadmap to the realisation of fusion energy", ISBN 978-3-00-061152-0, with kind permission of A.J.H. Donné)

As mentioned above, the operation of a fusion reactor based upon the tokamak concept is intrinsically pulsed, i.e., in intervals with interruptions. This results from the need for inducing a toroidally flowing electric current in the plasma chamber, in order to generate a magnetic field complementing the fields of the toroidal and poloidal field coils for confining the plasma. This is realized by ramping the current in the central solenoid coil located on the torus centreline axis. Thus, in principle a tokamak represents an electric transformer where the secondary side is depicted by a single current turn, i.e. the plasma. An alternative magnetic plasma confinement approach is the so-called stellarator concept. Here, no induced circular current is required; instead, a particular arrangement of twisted coils around the plasma ring provides the magnetic confinement. In contrast to a tokamak, a stellerator has no circumferential symmetry thus posing new engineering challenges; however, this concept does not suffer from plasma current driven instabilities. The most recent stellerator facility, Wendelstein 7-X at Greifswald, has successfully been set into operation with very promising results. While the stellarator development is lagging behind that of the tokamak by approximately one generation of facilities, a switch to this concept could be envisaged after DEMO depending on a further scientifically successful exploitation of Wendelstein 7-X. Similar to this parallel development on an alternative confinement concept, technological solutions for the major technological subsystems alternative to those pursued in main line of the DEMO conceptual design activity are being explored with a view to commercial attractiveness (energy efficiency of the plant, lifetime of components) and as fall-back solutions.

Currently, with the growing need of making new, sustainable energy solutions viable as early as possible, the European Roadmap is under revision. Both the possibility of accelerating DEMO via a stronger parallelization of developments, and of enhancing DEMO performance via an additional DT fusion test facility are being discussed.

Technical Systems and Challenges

There are numerous systems to be developed, and challenges to be tackled, around the central element of the burning plasma. An overview is indicated in

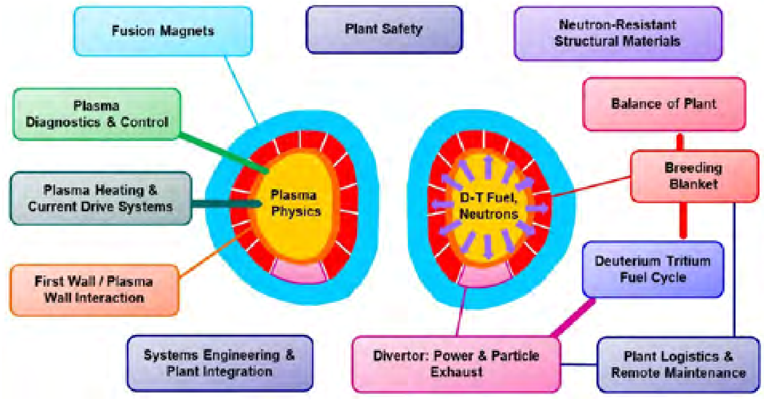

Fig. 4
Overview on the technical systems and challenges of magnetic confinement fusion power.
(Credit © Karlsruhe Institute of Technology, www.kit.edu)

Figure 4, and the different aspects are discussed in more detail above.

1 – Fusion Magnets

The fusion plasma is confined by strong magnetic fields. In the tokamak concept, it takes the shape of a torus, while the stellarator plasma has a more complex geometry. For ITER, three types of superconducting coils are being realized: the toroidal field coils which directly surround the plasma chamber, the central solenoid in the middle of the torus, and the poloidal field coils surrounding the torus horizontally on the outside. The superconductor materials used are NbTi and Nb_3Sn, with the latter posing a particular challenge, as the superconducting state is reached only after a heat treatment of the alloy, prohibiting the prior application of the Kapton® insulation. After the heat treatment, the material, however, is brittle and cannot be shaped, i.e. the shaping has to be done before heat treatment, and the Kapton® insulation afterwards. Still, a process has been developed and successfully implemented for the ITER toroidal field coils using this material. In the view of DEMO, however, it is not yet clear whether this technology can be extrapolated to the even larger dimensions and higher fields under consideration. Alternatively, high-temperature superconductor (HTS) solutions, so far neglected because of the price gap, could come into the play, and may even be the sole solution for larger, higher field stellarator magnets as compared to those of Wendelstein 7-X. Remarkable progress has been made in this field recently, e.g. the "uninsulated" HTS magnet coils presented by MIT. Nonetheless, although HTS offer unique opportunities, the knowledge on their neutron resistance is still in its infancies.

2 – Plasma Heating Systems

Plasma heating systems are required to bring the plasma to the temperatures of 100–150 million Kelvin necessary for the DT fusion reaction to take place, and, even during the "burning" phase with self-heating, to stabilize the plasma by localized deposition of energy. For ITER, three heating systems are foreseen in order to optimize the plasma scenario: Ion cyclotron resonance heating (ICRH), electron cyclotron resonance heating (ECRH) and negative ion based neutral beam injection (NNBI). While ICRH and ECRH use electromagnetic radiation to deposit energy in the ions and electrons of the plasma at the respective resonance frequencies determined by the magnetic field, NNBI injects high-energetic neutral fuel atoms, which are generated by first producing negative ions in a Caesium atmosphere, which then are accelerated and neutralized before getting injected into the plasma. The reason for this multi-step approach is that the penetration depth of injected ions is very limited due to the magnetic field confining the plasma. This can be overcome by using neutral atoms, which make their way deeper into the plasma before getting ionized. All the three heating systems for ITER now are in an advanced state of preparation. The goal for DEMO, in order to reduce complexity, is working with one heating system only. Given the drawbacks of NNBI (huge wall openings required vs. tritium confinement) and ICRH (trade-off between size of the antenna structures and sputtering effects), ECRH today seems to be the most promising heating system for DEMO.

3 – First Wall and Plasma-Wall Interaction

The plasma particles, ions and electrons, move along the magnetic field lines inside the confinement. Nevertheless, a certain fraction crosses the confinement border, still following a spiral trajectory and moving towards the intended exit point, the divertor. Even in normal operation, a small fraction of the plasma exhaust particles though hit the wall of the vacuum vessel, and this fraction can become large locally in the case of off-normal events, entailing sputtering and degradation of the wall facing the plasma, the so called "First Wall". In former plasma-physics experiments, carbon as a low-Z element that will be fully ionized in the plasma, and thus will not emit electromagnetic radiation from electronic state transitions, had been the material of choice for the First Wall. The presence of tritium in real fusion reactors, however, prohibits the use of carbon due to the possibility of forming tritiated hydrocarbons. For ITER, a different low-Z element, beryllium, thus had been selected and tested in JET. As Beryllium, unfortunately, is toxic for a part of the population, there are now considerations to immediately move to the First Wall material that will have to be used for DEMO and fusion power plants anyway, tungsten – a choice that is dictated by the sputtering and heat resistance of the material.

4 – Power & Particle Exhaust – the Divertor

A fraction of the plasma particles will regularly leave the confinement and move, still affected by the magnetic fields, parallel to the walls of the toroidal vessel to the intended exit point, the divertor. This depletion (and replacement with new fuel) is necessary to remove impurities as well as the helium "ash" of the fusion reaction. The divertor is a ring-shaped component at the bottom of the torus-shaped plasma vessel, consisting of the inner and outer target plates, the dome which inhibits back-diffusion of the neutralized particles into the core plasma before they can be pumped away, and a supporting structure. The highly energetic plasma particles will hit the target plates, releasing their kinetic energy. Thereby these plates will have to sustain heat loads of up to $20 MW/m^2$. For ITER, a solution has been developed using tungsten "monoblocks" enveloping a water-cooled copper-chrome-zirconium alloy tube, with the joining of the monoblocks and the tube being a particular challenge. To limit the heat load, and also the sputtering damage caused by highly-energetic plasma ions, divertor "detachment" is considered as a solution. By injecting suitable material (e.g., noble gases or nitrogen) into the plasma exhaust stream, neutralization and energy dissipation by electromagnetic radiation can be achieved spreading the heat load over a larger area. This is being intensely studied for DEMO, along with improved divertor geometries and materials combinations. A Divertor Test Tokamak (DTT) is currently under construction at Frascati, Italy.

5 – Plasma Diagnostics & Control

For stable and reliable operation of the plasma and thus the entire plant, the status of the plasma has to be monitored and controlled through the different phases, i.e., the ramp-up, the flat-top and the ramp-down, referring to the plasma temperature and current, respectively. From previous plasma physics experiments, quite a number of diagnostic techniques have been developed to detect the position, density and temperature distribution of the plasma, the plasma current as well as impurities, magneto-hydrodynamic (MHD) effects and instabilities. Many of these detect electromagnetic radiation (IR spectroscopy, bolometry, reflectometry, polarometry, …) and fields. Exhaust gas analysis complements the in-vessel sensors to evaluate the plasma gas composition and impurity content. For a neutron emitting fusion plasma, neutron and gamma detection and determination of the local reaction rate is important in addition.

The actors to react to the sensor signals, to maintain the plasma and steer it in the desired way, are the heating (and current drive) systems allowing the localized deposition of energy, as well as the fueling systems (gas or – frozen – pellet injection) as well as in-vessel magnet coils – besides the central solenoid and the poloidal field coils.

For ITER, there is an ongoing exercise to determine which sensor heads, mirrors, transmission lines etc. can withstand the neutron exposure at least for a reasonable time span, or how this can be extended. For DEMO, clearly the challenge is to develop control scenarios which can work with a severely reduced inventory of sensors suited for a harsh neutron environment – or can work in sufficient distance to it.

6 – Deuterium-Tritium Fuel Cycle

ITER and DEMO rely on the D-T fusion reaction, which requires the operation of a closed tritium cycle because of the radiotoxicity of this hydrogen isotope. Tritium has a half-life of slightly more than 12 years and can easily substitute protium (usual hydrogen) in water. 1µg of tritium incorporation (as water or in aerosols) comes close to the occupational limit of 20mSv per year, and is well above the exposure limit of 1mSv per year for the general public. The technology for the ITER fuel cycle has been developed and is now being transferred to industrial scale; it relies on cryo-pumping, purification and isotope separation processes which have to be operated with a certain inventory each. As tritium throughput for DEMO will have to be about two orders of magnitude higher than that of ITER (power and duty cycle scaling), extrapolation of the ITER processes is not possible. Assuming an (optimistic) tritium burn-up fraction of 2%, the overall tritium inventory in the systems could easily pile up to ~15 kg, and even more, if the burn-up fraction is lower. This would present a serious obstacle to licensing. Thus, new processes have to be introduced, and are already under development. One major advance will be replacing the discontinuous cryopumping by continuous processes using mercury pumps. Another breakthrough is expected from the application of membrane processes for "Direct Internal Recycling", i.e., re-directing ~80% of the unburnt deuterium and tritium from the plasma exhaust directly back into the plasma, while the helium and other impurities to be removed stay in the remaining exhaust gas stream which will go the purification and separation systems, thus reducing the tritium load and inventory there in proportion.

7 – Tritium Breeding Blanket

ITER will receive external tritium supply, which can be provided from the tritium production in CANDU type reactors. For DEMO and subsequent fusion power plants, after having been equipped with a tritium start-up inventory of a few kg, tritium self-sufficiency is mandatory, also limiting the transportation risks for the hazardous nuclide. This can be achieved by so-called tritium breeding blankets around the plasma, but inside the vacuum vessel, making use of the reaction:

$$^{6}\text{Li} + \text{n} \quad \rightarrow \quad \text{T} + \text{He} + 4.8\ \text{MeV}$$

Theoretically, each neutron produced by a D-T fusion reaction thus can generate a new tritium atom. In reality, however not the entire area of the plasma facing wall can be occupied by blankets. Moreover, the blankets require structural materials. Thus, many neutrons undergo nuclear reactions or are absorbed within matter not contributing to tritium breeding. Hence, neutron multiplication is necessary to compensate for this. As neutron multiplier materials, beryllium (or Be-rich compounds) or Pb are being considered. In the European fusion program, two combinations are being developed for DEMO, i.e., the so-called liquid breeder, a eutectic mixture of lithium and lead which will be pumped through the blanket structure, and the "solid breeder" variant consisting of lithium ceramics pebble beds surrounded by $TiBe_{12}$ structures. For both approaches, test blanket modules are foreseen in ITER.

Beyond breeding tritium, the breeding blanket has the equally important function of transferring the heat generated by the neutron moderation and the nuclear reactions to a suitable primary coolant at a high temperature level for conversion into electricity. In the European program, two coolant options are being developed, i.e., water and helium. The water variant is deemed to be more mature because of the experience from the PWR plants. Nevertheless, radiation-induced chemistry will be different because of the different neutron energy spectrum with much higher energies in fusion. Moreover, the PWR range of 285 °C – 325 °C actually is not compatible with the operation temperature range of the structural material so far developed for fusion, EUROFER, which is between ~ 350 °C – 550 °C as discussed below. Helium can exploit the full range of this temperature window, giving access to higher efficiency due to the higher temperature level and the higher temperature rise - even though, as a compressible medium with less heat capacity than water, it will need higher pumping power -, and will avoid any coolant chemistry problems. However, components cannot be bought off the shelf but will have to be developed, while prototype facilities already exist.

Last but not least, another important function of the breeding blanket is shielding the superconducting magnets behind the vacuum vessel from the fusion neutrons.

8 – Neutron-Resistant Structural Materials

The D-T fusion reaction intrinsically produces neutrons of 14.1 MeV energy. This is an order of magnitude higher than in "fast" fission reactors and much higher than the average neutron energy in water-moderated reactors. Hence, different damage rates and damage mechanisms in the exposed materials and components inside the plasma vessel (breeding blanket, divertor) have to be considered. Similar to fission neutrons, fusion neutrons cause displacement damage, i.e., displacement cascades propagating from the primary knock-on atom through the material, with the consequences being proportional to the deposited neutron energy. The exposure level is measured in "displacements per atom" (dpa). A single neutron can cause, depending on the deposited energy, thousands to millions of displacements, with most of them relaxing to the original or an equivalent lattice position still within the propagation time of the cascade. Nevertheless, the remaining displacements accumulate. Furthermore, the neutrons can react with the nuclei of the structure, resulting in transmutation and activation. In transmutation reactions, light nuclei (H, He) are ejected; the resulting atoms can be trapped at grain boundaries and cause embrittlement. Activation reactions cause radioactivity, which has to be limited to the minimum possible level and should decay fast to definitely avoid the need for a long-term repository.

Given the fact that the activation of pure iron under fusion conditions will entail a decay time of ~100 years until recycling will be possible, the reduced-activation ferritic-martensitic steel EUROFER has been developed, avoiding / replacing alloy elements which could generate radioactive nuclides with long decay times like Ni. The material is well characterized with fission reactor neutrons, resulting in an operation temperature range from 350 to 550°C under neutron irradiation. Below this range, irradiation embrittlement will move the brittle-to-ductile transition to values above room temperature, and above, yield strength and creep resistance decrease significantly. Developments on alternative steels for a lower (water cooling) or a higher temperature range (helium cooling) are ongoing, yet neutron irradiation results so far are preliminary only. In general, the lack of the possibility of material irradiation with a fusion-relevant spectrum, i.e., 14 MeV neutrons, at substantial flux is an obstacle in the development and qualification of materials for the blanket and the divertor. To overcome this, construction of an accelerator-based neutron source, "DONES", has now been started at Granada, Spain. Still, it will take about 10 years until neutron exposures can start there and the necessary neutron dose rates can be accumulated.

As an estimate, the most exposed part of the breeding blanket will accumulate 20 – 30 dpa per year, depending on the layout of the power plant. The neutron resistance will determine the lifetime of the component in the reactor and hence the economic viability (see below).

9 – Plant Logistics and Remote Maintenance

Due to the neutrons produced in the fusion reaction, the components in the plasma vessel will become activated, and will require remote handling for maintenance and exchange. For ITER, this concerns the divertor elements at the bottom of the reactor vessel, as well as the First Wall panels covering it at the inside. These operations will be provided by dedicated equipment that will access the inside of the vessel through ports, i.e., openings in the vessel usually closed by port plugs. Further port plugs serve as inserts for test modules for breeding blanket systems, and for the diagnostic equipment needed. As the port plugs "see" the fusion neutrons, their exchange has to be done by remote maintenance, too. While the divertor and (few) port operations for DEMO could be very similar to those for ITER, the situation with the breeding blankets is completely different. Here, we have components of steel, filled with breeder and neutron multiplier materials, which, because of the stopping length of the neutrons, will be 1–1.5 m thick. Single sectoral, banana-shaped elements will weigh tens of tons. The current plan is to exchange them by lifting them through ports at the top of the vessel. Alternatively, there could be smaller compartments, reducing the payload for the remote handling system, however increasing substantially the number of pipe connections which have to be opened and re-welded. The development of a suitable, licensable remote maintenance system for DEMO, and the necessary tools, still represents a major challenge. The duration and efficiency of these operations, in relation to the in-vessel lifetime of the components, will have a major impact on the availability of DEMO and any subsequent power plant. Thus, similarly to increasing blanket and divertor lifetime as much as possible, efficient, well-coordinated remote maintenance operations are key to the overall efficiency of the plant. To this end, an intelligent, integrated planning of the individual remote maintenance operations, taking into account the availability of tools, space requirements, pathways between the reactor vessels and the hot cell, storage space and operators, i.e., an integrated plant logistics model, has to be developed to allow rigorous optimization.

10 – Energy Conversion – Balance of Plant

As already mentioned, electricity generation from fusion is not just an extrapolation from fission. The pulsed operation (pulses of several hours with dwell times of 10 -15 minutes are targeted for DEMO) will necessitate intermediate heat storage. Currently, molten-salt systems with different parameters for water or helium as the primary (blanket) coolant are being considered, with water, offering the lower temperature shift, requiring the larger storage. Complementary, and with the aim to reduce the intermediate storage requirement, steam turbines that would allow operation with changing load levels are under consideration. In any case, the dynamic behaviour of such combined conversion systems for the different load cases has to be understood. To this end, pilot facilities for the two different primary coolants are under construction at Brasimone, Italy, and Karlsruhe, Germany. Furthermore, the blankets are not the only source of heat. Other sources are the divertor and the plasma heating systems (with the part of their energy consumption that is not sent to the plasma), of course at different temperature levels. It is a challenge to integrate these into the overall conversion cycle - as is the electricity supply for the different plant systems, e.g., the cryo-plant, the magnets and again the heating systems.

Once the stellarator concept will be mature enough to be developed into a power plant, the need for an intermediate heat storage may lose importance or may even disappear. Still, intermediate transfer to a secondary coolant will be necessary to avoid tritium diffusion and/or radiolysis products migration into the conversion systems.

11 – System Engineering and Plant Integration

As shown so far, a fusion reactor / power plant will consist of quite a number of components / systems with different functions, each of them with a parameter range for operation with optimum and limiting values, in quite some cases depending on the material choice (breeding blanket, divertor, first wall, magnets, sensor and actuator systems). These components will not operate in isolation, but there are numerous interfaces between them, thus also relating the respective operation conditions and the performances. The system engineering task for DEMO and subsequent fusion power reactors first of all is to systematically understand the interfaces among the different components and their mutual impact, and to develop tentative, conceptual integral plant designs. At the appropriate level of maturity and characterization, this in the first place will lead to favourable technology choices.

Once the choices are made, the different components have to be integrated into a detailed, viable plant design. This will be supported by the development of a system code integrating the models of the components and their interactions into a single, powerful software tool for the optimization of the overall design and parameter choices. The development of such tool is already being addressed in the European program.

12 – Plant Safety & Licensing

Licensing of ITER, DEMO and any subsequent fusion power plant will require an encompassing safety demonstration. Above all, the confinement of radionuclides, in particular tritium, has to be guaranteed for operation and maintenance as well as for management and intermediate storage of radioactive waste. The most important first operational static confinement barrier is the vacuum vessel with its port extensions, but according to the defense-in-depth principle, further static and dynamic confinement barriers need to be implemented. An exhaustive set of accidental scenarios with lead cases enveloping minor accidents/incidents, and the corresponding protection measures, have to be defined. However, the latter are highly dependent on the design options chosen, so at present a design analysis is performed based only on the SSG guidelines formulated by the IAEA.

The licensing exercise for ITER so far has shown that transferring nuclear fission based regulations to a fusion plant might not be adequate due to differences in physics and hazard potential. Fission licensing regulations are adapted to risks that do not exist in fusion, in particular power escalations caused by reactivity events associated with potential consequences of the release of a high radionuclide inventory, which also is not given in the case of fusion. Using this framework for fusion would entail setting wrong priorities. Instead, an adapted licensing framework for fusion plants will have to be developed. This is already being actively addressed in the US and the UK; the IAEA has started a related initiative, and also in Europe and in Germany there are signals that the need for a specific fusion licensing framework has been understood at the political level.

Summary

There are many technical challenges on the way to fusion power. Among these, the interplay and integration of the different subsystems into one coherent plant design probably is the biggest one. All the areas where specific solutions are required are being addressed now within the European fusion program, of course, at different levels of maturity. At present, the finalization of the solutions required for ITER has priority. Nevertheless, in the sense of early deployment of fusion, other aspects like fusion-neutron-resistant materials or the tritium breeding blanket, must not be neglected. A specific licensing framework for fusion plants will be necessary.

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