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Concluding remarks

Fusion power undoubtedly offers the prospects of an almost inexhaustible source of energy for future generations. The design and R&D of future fusion reactor concepts is expected to benefit largely from the experience gained in the design, licencing, construction and operation of ITER. However, harnessing fusion energy and deploying reliable magnetic confinement fusion power plants is still a distant goal and relies on our ability to overcome the remaining design, physics and engineering gaps and development needs for key fusion technologies that are essential for reliable and efficient operation of a fusion reactor.

This special issue describes the outcome of the DEMO pre-concept design and R&D effort that was conducted in Europe from 2014 until 2020 to advance the technical basis of the DEMO design. This work is part of a staged design approach that has brought clarity to a number of critical plant design issues that are described in this issue and that have provided a clear path for urgent R&D. In the initial phase, emphasis was placed on 1) the implementation of a focussed technology R&D and system design studies, driven by the requirements of the DEMO plant concept and responding to critical design, feasibility, safety and nuclear integration risks; 2) the evaluation and impartial assessment of multiple design options and parallel investigations for systems and/or technologies with high technical risk or novelty; 3) the evaluation of the foreseeable technical solutions, together with a technology maturation and down-selection strategy to bound development risks by adopting structured and transparent gate reviews. The gate review conducted at the end of 2020 to evaluate the technical work conducted and review the implementation plan for DEMO beyond 2020 is also detailed. This proved to be an invaluable process for both the project and its stakeholders, resulting in a strengthening of the plan forward.

1. Main lessons learned in the initial effort to design demo

1.1. Formidable integration challenges exist, made even more challenging by the nuclear regulatory environment

It is important to acknowledge that work conducted to date has raised the awareness of the importance of the integration aspects in the design process. The design of DEMO and any other fusion reactor, is affected by a high degree of complexity/system interdependencies and multiple design drivers across various systems that impact the design and performance of the plant. There are several design choices that pervasively affect the overall design layout and the performance of the nuclear plant and its maintainability and safety, because of the interfaces with all key nuclear systems. These challenges must be addressed with robust and reliable solutions because fusion remains a nuclear technology and as such will be scrutinised by a nuclear regulator. Recently, there have been many discussions about making fusion power producing devices smaller, cheaper, and faster, but the truth is that there is no silver bullet to solve the complex nuclear design integration problems of a fusion device. It should also be noted that the increased regulatory oversight after Fukushima is responsible for significant cost increase of many nuclear installations under construction (including ITER).

1.2. Large knowledge gaps and uncertainties in key reactor technologies not fully demonstrated by ITER that require further R&D

The DEMO design and R&D activities in Europe are benefitting largely from the experience gained from the design, licencing, and construction of ITER, which remains the crucial machine on which the validation of the DEMO physics and part of the technology basis depends. Nevertheless, there are outstanding physics, materials and engineering challenges, with potentially large gaps beyond ITER that need to be urgently addressed and that were clearly identified during the gate review process. In particular, the design of the DEMO breeding blanket, the qualification of radiation-hardened structural materials that would retain their mechanical properties and guarantee structural integrity under intense neutron (much higher in DEMO than in ITER), the remote maintenance for the in-vessel components, the design of the nuclear buildings, the development of a plasma scenario and the strategy of the power exhaust were all recognised to be of crucial importance and work must be prioritised in these areas.

1.3. Design dealing with uncertainties in physics and technology

Significant uncertainties in fusion science and engineering will persist throughout the Concept and Engineering Design Phases – in some cases for decades to come. The importance of managing complexity and uncertainty was identified and a preliminary adequate systems engineering framework has been implemented and this will be developed further in future, with the aim of establishing a robust, repeatable, and traceable decision-making process for the DEMO architecture. Traditional systems engineering practices have tended to be developed for

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individual systems with relatively closed boundaries: clear and detailed requirements, few – if any – complex interfaces, few external factors of influence, etc. DEMO, however, is altogether a very different type of system; there are few known and detailed requirements, numerous interfaces and interdependencies, and the device is in general characterised by high complexity and uncertainty. The direction of the DEMO architecture will need to be continually assessed in the Concept Design Phase to address these uncertainties and decisions will once again have to be made based on incomplete information.

1.4. Lack of a nuclear design integration and a nuclear safety culture

Radiation shielding and safety play an overwhelming role in the design, and propagation of safety requirements on the design should not be postponed. An early engagement with licensing regulators would be very useful to understand and tackle potential safety implications through design amelioration.

1.5. Uncertain future of nuclear industry

During the last 20 years in Europe it was assumed that parallel advanced development in areas of Balance of Plant, power extraction and conversion of nuclear systems and high temperature structural materials would have occurred in fission industry, in particular from the development of advanced fission systems (i.e., Gen. IV). Unfortunately, one has to acknowledge the lack of this expected parallel development and, at least in Europe, there is an ongoing consolidation of nuclear vendors, and certified companies with nuclear technology competence and expertise. In addition, GEN IV development plans have slowed down or halted and is difficult to predict significant developments in the near and medium term. This could have an adverse impact on fusion development.

1.6. Tritium availability and control

Achieving tritium self-sufficiency will be an unescapable requirement for any next-step fusion nuclear facility beyond ITER. However, no fusion blanket has ever been built or tested. Hence, its crucial integrated functions and reliability in DEMO and future power plants are by no means assured. However, the program in Europe benefits from many years of design and R&D, primarily carried out in European Fusion Laboratories. In addition, ITER presents a first and unique opportunity to test the response of representative component mock-ups, specifically called Test Blanket Modules (TBMs) at relevant operating conditions, in an actual fusion environment, albeit at very low neutron fluences.

As an example, a 2GW fusion power DEMO is expected to consume around 110 kg of tritium per full power year (fpy). The large majority of this tritium must be produced by the reactor itself, and this clearly underscores the indispensable requirement for the breeding blanket to produce and enable extraction of the bred tritium to achieve tritium self-sufficiency (i.e., it must produce its own fuel). However, there is the need to start-up the reactor at the very beginning of operation with a sufficient amount of tritium provided by external sources (5–10 kg). This raises a need to better understand and monitor the future availability of tritium and understand the impact of limited resources on the timeline of DEMO. However, there is essentially very little that the fusion community can do to exert an effect on the supply side, as tritium is a by-product of the operation of some specific fission reactors and not the primary economic incentive. Defence stockpiles of tritium are unlikely ever to be shared, and commercial CANDU operators will not alter their plans just to sell more tritium for the start-up of the first fusion power plants. In the short-term it is recommended to monitor the production of tritium in Heavy Water Reactors and estimate the commercially available supply. If, at some point in the future, it looks as though the demand for DEMO, alongside the other tritium consuming devices foreseen globally, will exceed the supply from CANDUs, then action would have to be taken. It is likely that production of significant amounts of tritium from a dedicated source would be very expensive and take a long time. The "tritium window" as it was once defined by Paul Rutherford [1] is not open indefinitely. Based on current estimates, we believe it would be open until around 2050–60, after which it closes quite rapidly, unless the future of the CANDU reactor program turns out much more favourably than could presently be expected. Any program strategy that substantially delays DEMO places fusion at risk, by allowing the unique and effectively irreplaceable tritium resource to decay to levels which may be insufficient to complete fusion's technological development.

2. Defining the plan forward

The considerations above have played a major role in defining the plan forward in Europe. The main elements of this plan that are described in this special issue include:

- Establish a centralised Design Team (DCT) capable of more rapid design cycles for evaluation of design directions. The DCT is foreseen to advance the design basis (physics and technology) of a DEMO fusion power plant, by implementing an agile architectural design capability, impartial analysis of options, and quick access to the expertise distributed in the EU fusion laboratories, universities and industry. This is needed to ensure the rapid convergence towards a feasible DEMO plant architecture.
- Refocus the physics R&D for DEMO towards developing an attractive and robust reference plasma scenario (no-ELMs, low disruptivity, etc.).
- A focussed multi-year Technology R&D Maturation Plan to address major risks: breeding blanket, material R&D and qualification; Remote Maintenance, etc.
- Strengthen nuclear design integration and a nuclear safety culture during design phases.
- Continue Technology Readiness Assessments conducted by external independent experts (including IO and F4E) and industry.
- Develop improved modelling tools to address critical physics and engineering issues.
- Continuous development of project management culture.
- Incorporate lessons learned from the ITER design and construction.
- Build and maintain relationships with industry and embed industry experience in the design to ensure early attention is given to industrial feasibility, costs, nuclear safety and licensing aspects.
- Consolidate international collaborations to fill critical gaps.

Finally, it should be noted that the goals and the progress to achieve them are linked to the availability of adequately skilled human resources and there is a real risk that this becomes a critical bottleneck. The fusion program is ageing rapidly and a first generation of fusion pioneers has left or is leaving the field in the years to come. There is a need to find ways to maintain the enthusiasm that has been the pride of the fusion area and that has attracted outstanding people to work in the field. There is shortage of engineering skills in fusion. We have specialists, but lack designers, i.e. people familiar with tokamak/systems design and that have a systemic view of the plant. Unless we continue to attract bright minds for the future, fusion will surely wither. Education and training in fusion must play an important role in each programme. In

Europe there are over 700 active PhD students been trained and an extensive number of young engineers including 20 awarded a dedicated EUROfusion Engineering Grant per year. Alongside the dedicated education and training programmes, university programs and fusion laboratories are absolutely vital to sustain the worldwide effort to develop fusion and breed the new generation of fusion scientists and engineers. If the DEMO Engineering Design efforts starts too long after ITER is delivered, a highly skilled and experienced workforce will be lost to other industries, with an unavoidable brain drain and loss of lessons learned.

Reference

[1] P. Rutherford, "The Tritium Window," informal PPPL report, 1999.

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