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FIELD GRAND CHALLENGE
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# Grand Challenges in Nuclear Engineering

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The 1992 United Nations Rio de Janeiro declaration (United Nations, 1992) states that "*Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.*" This brief affirmation highlights the implications from the impact of growing human population on the environment (Cartledge, 1995; MacKay, 2009), manifested in the notion of climate emergency (Ripple et al., 2020). Nuclear power offers progressive options to mitigate global warming and other effects of climate change, with the International Energy Agency (IEA) suggesting that the nuclear energy generation currently eliminates between 1.3 and 2.6 giga-tonnes of $CO_2$ emissions from the power sector each year, depending on whether it is assumed that it replaces gas- or coal-fired power plants.

The IEA's 2015 Technology Roadmap (IEA, 2015) report noted that to meet the Paris Agreement target of global temperature not rising by more than 2°C, the world nuclear power generation capacity needs to increase to 930 GW in 2050. For comparison, the Smart Energy Europe analysis projected the European nuclear power generation capacity in 2050 to the level of 105 GW (Connolly et al., 2016), against the current levels of 61.3 GW in France, 9 GW in the United Kingdom, raising to 24 GW by 2050 (UK Government, 2022), and 4.3 GW in Germany, down from the 2021 level of 7.4 GW. Comparing these figures and the data for other geographical areas with the projected world total nuclear generation capacity, we observe that many new power plants are expected to be constructed in the countries where nuclear power generation technology and engineering have so far been largely unknown. This expected expansion will involve a broad range of engineering and technological challenges spanning the manufacturing of reactor components, the fabrication and extraction of fuel, the development of efficient coolant and heat transfer technology, the reactor assembly schedules, the establishment of supporting hot cell and waste processing facilities, and the technology for scheduled and unscheduled remote maintenance and operation, enabling the reactor systems to reliably function over long periods of time.

All the presently operating commercial nuclear reactors use fissile nuclear fuel, containing isotopes of uranium and other actinide elements. On the other hand, fusion power generation, an area of active development and innovation worldwide, aims to use light fusable chemical elements, for example the deuterium and tritium isotopes of hydrogen (Pearson and Takeda, 2020; Prager and Najmabadi, 2020). Fusion technology presents a range of scientific and engineering challenges that need to be addressed to enable the construction of a fusion power plant (Chapman and Walkden, 2020). These include the development of a reliable and safe tritium and deuterium extraction and handling technology, the integration of structural and functional materials in a power plant design, and the extensive use of remote handling and robotics in the maintenance of a power plant. But first and foremost, it is the development of robust means for controlling the high temperature plasma (Kodama et al., 2001; Hender et al., 2007), either in a magnetic confinement device or in a pulsed, for example a laser-driven, fusion system that presents an outstanding challenge to the fusion power plant engineering.

The fundamental considerations involved in the assessment of nuclear power are its economic competitiveness against the power sources using coal and gas, or the renewable sources like solar and wind power (Alonso et al., 2016), and its environmental impact (Pigford, 1974; Danish et al., 2022).

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The economic factors have until recently been driving a gradual decline of the global share of nuclear electricity generation from 17.5% in 1996 to 10% in 2019 (Ramana, 2021). However, the increasing cost of fossil fuels and the global warming resulting from the present unsustainable level of $CO_2$ emissions, and the intermittent nature of solar and wind power generation as opposed to the *firm energy* delivered by the nuclear or hydroelectric power plants at a high level of stability of supply, appear to be shifting the balance, making nuclear power generation increasingly more attractive.

Among the environmental effects of nuclear power generation, the management, storage, and eventual disposal of nuclear waste–a significant part of which can be referred to as not fully used nuclear fuel–is guided by the internationally accepted standards (Kim et al., 2011). Annually, a 1 GW nuclear power plant generates several cubic metres of high-level radioactive waste requiring active cooling, and 500–1,000 cubic metres of low-level waste, and this waste must be disposed of in such a way that it imposes minimal burden of care on later generations. As a part of the disposal process, a proof beyond reasonable doubt is required that the increase in radiation due to the deposited material is a small fraction of the natural background level (Roberts, 1990). Fusion power plants are also expected to produce radioactive materials, requiring reprocessing or disposal, with a notable difference that fusion power, unlike fission, does not involve the use of actinides. A suitable choice of structural materials can further reduce the waste burden. Inventory calculations, included in the fusion power plant design process, can predict the evolution of chemical composition, activation, the decay heat of materials exposed to fusion neutrons, as well as the gamma-dose and neutron shielding requirements, maintenance schedules, aiding the recycling and disposal prospects (Gilbert et al., 2017).

Large light water reactors (LWRs) have been selected by the utility companies around the world as their primary choice of nuclear power plants because of their reliability, the economy of scale, and the fact that the construction of an LWR involves commonly available materials such as water, concrete, and stainless steel, offering the advantage of extensive know-how and enabling the rapid adaptation of existing technologies to the manufacturing of reactor components (Murakami, 2021).

The less well established nuclear power generating options presently attracting interest are the Small Modular Reactors (SMR) (Locatelli et al., 2014; Schaffrath et al., 2021), Fast Reactors (FRs) (Merk et al., 2015), especially the sodium-cooled FRs that have been developed and operated since the 1970s, and the high-temperature gas-cooled reactors that could drive hydrogen production (Jaszczur et al., 2016) or water desalination (Al-Othman et al., 2019). SMRs can replace the coal-fired power plants and be integrated with renewable sources into an electricity grid, ensuring the stability of supply and balancing the fluctuating wind and solar power generation (Liu et al., 2022). A sodium-cooled fast reactor system, a front-runner among the Generation IV reactors (Ramana, 2021), involves a fast-neutron-spectrum reactor and closed fuel recycling technology, enabling the improved use of nuclear fuel, management of high-level nuclear waste and, in particular, the utilization of plutonium and other actinides (Aoto et al., 2014). As recent practical steps, in February 2021 the BN-800 sodium-cooled fast reactor unit at the Beloyarsk nuclear power plant was connected to the grid, operating solely with uranium-plutonium fuel (BN-800, 2021) and, in December 2021, the world's first high-temperature pebble-bed Generation IV reactor was launched at the Shidaowan nuclear power plant (CNNC, 2021).

What are the key scientific, technological and engineering challenges associated with the current state of development of nuclear power? The generic new features of advanced nuclear fission reactors were identified in a recent review by the Office of Nuclear Energy of the US Department of Energy. They include the requirement of no or minimal operator intervention in the event of an accident, the reduction of the amount of spent fuel requiring disposal, and the development of reactor technologies that can re-use the spent nuclear fuel. Also, new reactors are expected to utilize the heat directly for industrial processes, including hydrogen production and water desalination, and to enable load following, to integrate them into the electricity grid to support the intermittent power sources like solar and wind. Finally, if the aim of capital cost reduction resulting from the economy of scale can be achieved, this should enable the broader deployment of reactors in a modular form. Fusion power plants are expected to satisfy similar requirements (Federici et al., 2021), with the added engineering challenge associated with designing, constructing and operating the largest ever superconducting magnets (Sgobba et al., 2022). A number of major fusion engineering challenges have been already addressed in connection with the design and construction of ITER (Merola et al., 2014), and the increasing focus on building demonstration fusion power plants of different design, supported by private and public investment worldwide, is expected to help identify and address the challenges that are still outstanding.

*Frontiers in Nuclear Engineering* is a multi-disciplinary, open-access scientific journal providing the platform dedicated to the publication of ideas, reports, methods, techniques and data that can help advance the broad field of nuclear engineering, and enable addressing the above challenges. The aim of the journal is to encourage information exchange and collaboration between scientists, stakeholders, and civil society to support the environmentally sustainable and safe use of nuclear power.

Whereas above we emphasized the use of nuclear energy as a carbon-free power generation option, this by no means defines the entire range of applications of nuclear engineering. Nuclear reactors and accelerator-driven systems produce specialized isotopes for medical applications. X-ray, magnetic resonance imaging (MRI) and positron emission tomography (PET) scanners have revolutionised modern medicine by providing the means for *in situ* high-resolution imaging of organs in a human body. The development of advanced medical devices is a timely noble challenge to nuclear engineering. An example of application of nuclear engineering on a very different length scale, the small radioisotope general-purpose heat sources powered the *Voyager* probes that have now reached beyond the boundaries of the Solar system, and enabled other space missions including the martian *Curiosity* rover.

The development of nuclear engineering is expected to stimulate advances and discoveries in the related scientific disciplines, including the remote handling and robotics essential for the maintenance and operation of nuclear reactors, the use of new specialized materials, and the development of new mathematical methods and algorithms for computer modelling, to improve the understanding of operating conditions and safety of nuclear reactors. The concept of a virtual reactor REVE (REacteur Virtuel d'Etudes) proposed at the turn of the century (Jumel et al., 2000) has now evolved into the notion of a digital twin, a virtual replica of a reactor integrating the sensors, data, computers, and mathematical models that is expected to enable operating a reactor at an unprecedented level of monitoring, control, training, supervision and security (Yadav et al., 2021).

An even greater challenge is associated with the effort to design an advanced fission or a fusion power plant, where the predictive assessment of operating conditions and reliability of reactor components necessarily requires the development and application of multiscale multi-physics computer simulations (Eyre and Matthews, 1993; Gaston et al., 2009, 2015) that include models for the effect of neutron irradiation on materials (Cui et al., 2018; Mason et al., 2021; Reali et al., 2022). To ensure the success of macroscopic finite element simulations, the underlying microscopic models must be able to interpolate *and* extrapolate over a broad range of environmental parameters and conditions. The challenge here involves optimising the balance between the generation of input data for the data-driven algorithms (Schmidt et al., 2019), which is a difficult issue in its own right as the expected conditions in a reactor are hard to reproduce in a laboratory, and the fundamental physical content, defining the quality and range of validity of a model (Finnis, 2003). A particular question concerns the digital interfaces between the various models involved in an integrated numerical representation of a reactor, where the verification, validation and uncertainty quantification of coupled neutron transport and thermo-hydraulic models in the context of LWR design and safety analysis were reviewed in (Ivanov and Avramova, 2007; Avramova and Ivanov, 2010; Avramova et al., 2021).

Nuclear engineering involves the invention and development of means for exploiting and controlling the energy confined in the atomic nuclei by one of the most fundamental natural phenomena, the strong force (Salam and Taylor, 1990). It is hardly a surprise that the subject proves challenging and demanding, since the sub-atomic origin of nuclear energy makes the problem inherently complex and multi-scale.

The starting point for nuclear engineering is the understanding of nuclear reactions, the transport of neutrons, other sub-atomic particles and electromagnetic radiation, and their interaction with materials and effect on reactor components. This raises the question of quantitative observation, linked with modelling and simulation of operating conditions in a nuclear engineering system. Given the statistical and stochastic nature of nuclear interactions, the probabilistic aspects of structural integrity of nuclear reactors emerge as one of the important areas in reliability and safety analysis (Chavoshi et al., 2021).

The efficient use of nuclear fuel is not only an economic consideration but also an environmental challenge since it is the partially burnt fuel that produces the high level waste. The efficient use of fuel involves not only the optimal choice of its chemical composition and microstructure (Tonks et al., 2017) but also the selection of high-performance cladding materials and operating conditions. The development and qualification of cladding (Preuss, 2021) and advanced structural nuclear materials (Cabet et al., 2019; Zinkle et al., 2019; Rieth et al., 2021) is an area of research where *Frontiers in Nuclear Engineering* will help stimulate the interdisciplinary collaboration between materials scientists and engineers.

Finally, we would like to highlight an overarching challenge that has a bearing on all current and future endeavours in the field of nuclear engineering. The challenge is in its relation to society, through understanding, communication and education. Nuclear science and engineering is an advanced field, where applications are based on the detailed knowledge and appreciation of complex nuclear phenomena, often occurring in extreme conditions. The detailed rational explanation and communication of the concepts and data, the critical assessment of risks and benefits, and the advanced means for the visual and interactive communication of fundamental nuclear ideas and notions, bridging science and art, are among the essential topics that *Frontiers in Nuclear Engineering* aims to promote and inspire.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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