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# **Grand Challenges in Nuclear Engineering**

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# Grand Challenges in Nuclear Engineering

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## 2 ABSTRACT

3 **Keywords:** nuclear engineering, nuclear power generation, fusion and fission, reactor design, Small Modular Reactor, firm energy,  
4 nuclear fuel, waste disposal, systems engineering, nuclear materials, deuterium and tritium, radiation effects, computer modelling and  
5 simulation, uncertainty quantification

6 The 1992 United Nations Rio de Janeiro declaration (United Nations, 1992) states that “*Human beings are*  
7 *at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in*  
8 *harmony with nature.*” This brief affirmation highlights the implications from the impact of growing human  
9 population on the environment (Cartledge, 1995), manifested in the notion of climate emergency (Ripple  
10 et al., 2020). Nuclear power offers progressive options to mitigate global warming and other effects of  
11 climate change, with the International Energy Agency (IEA) suggesting that the nuclear energy generation  
12 currently eliminates between 1.3 to 2.6 giga-tonnes of CO<sub>2</sub> emissions from the power sector each year,  
13 depending on whether it is assumed that it replaces gas- or coal-fired power plants.

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

28 All the presently operating commercial nuclear reactors use fissile nuclear fuel, containing isotopes  
29 of uranium and other actinide elements. On the other hand, fusion power generation, an area of active  
30 development and innovation worldwide, aims to use light fusible chemical elements, for example the  
31 deuterium and tritium isotopes of hydrogen (Pearson and Takeda, 2020; Prager and Najmabadi, 2020).  
32 Fusion technology presents a range of scientific and engineering challenges that need to be addressed  
33 to enable the construction of a fusion power plant (Chapman and Walkden, 2020). These include the  
34 development of a reliable and safe tritium and deuterium extraction and handling technology, the integration

35 of structural and functional materials in a power plant design, and the extensive use of remote handling  
36 and robotics in the maintenance of a power plant. But first and foremost, it is the development of robust  
37 means for controlling the high temperature plasma (Hender et al., 2007; Kodama et al., 2001), either in  
38 a magnetic confinement device or in a pulsed, for example a laser-driven, fusion system that presents an  
39 outstanding challenge to the fusion power plant engineering.

40 The fundamental considerations involved in the assessment of nuclear power are its economic  
41 competitiveness against the power sources using coal and gas, or the renewable sources like solar and  
42 wind power (Alonso et al., 2016), and its environmental impact (Pigford, 1974; Khan et al., 2021). The  
43 economic factors have until recently been driving a gradual decline of the global share of nuclear electricity  
44 generation from 17.5% in 1996 to 10% in 2019 (Ramana, 2021). However, the increasing cost of fossil  
45 fuels and the global warming resulting from the present unsustainable level of CO<sub>2</sub> emissions, and the  
46 intermittent nature of solar and wind power generation as opposed to the *firm energy* delivered by the  
47 nuclear or hydroelectric power plants at a high level of stability of supply, appear to be shifting the balance,  
48 making nuclear power generation increasingly more attractive.

49 Among the environmental effects of nuclear power generation, the management, storage, and eventual  
50 disposal of nuclear waste - a significant part of which can be referred to as not fully used nuclear fuel - is  
51 guided by the internationally accepted standards (Kim et al., 2011). Annually, a 1 GW nuclear power plant  
52 typically generates several cubic metres of high-level radioactive waste requiring active cooling, and 500 to  
53 1000 cubic metres of low-level waste, and this waste must be disposed of in such a way that it imposes  
54 minimal burden of care on later generations. As a part of the disposal process, a proof beyond reasonable  
55 doubt is required that the increase in radiation due to the deposited material is a small fraction of the natural  
56 background level (Roberts, 1990). Fusion power plants are also expected to produce radioactive materials,  
57 requiring reprocessing or disposal, with a notable difference that fusion power, unlike fission, does not  
58 involve the use of actinides. A suitable choice of structural materials can further reduce the waste burden.  
59 Inventory calculations, included in the fusion power plant design process, can predict the evolution of  
60 chemical composition, activation, the decay heat of materials exposed to fusion neutrons, as well as the  
61 gamma-dose and neutron shielding requirements, maintenance schedules, aiding the recycling and disposal  
62 prospects (Gilbert et al., 2017).

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

68 The less well established nuclear power generating options presently attracting interest are the Small  
69 Modular Reactors (SMR) (Locatelli et al., 2014; Schaffrath et al., 2021), Fast Reactors (FRs) (Merk et al.,  
70 2015), especially the sodium-cooled FRs that have been developed and operated since the 1970s, and the  
71 high-temperature gas-cooled reactors that could drive hydrogen production (Jaszczur et al., 2016) or water  
72 desalination (Al-Othman et al., 2019). SMRs can replace the coal-fired power plants and be integrated with  
73 renewable sources into an electricity grid, ensuring the stability of supply and balancing the fluctuating  
74 wind and solar power generation (Liu et al., 2022). A sodium-cooled fast reactor system, a front-runner  
75 among the Generation IV reactors (Ramana, 2021), involves a fast-neutron-spectrum reactor and closed  
76 fuel recycling technology, enabling the improved use of nuclear fuel, management of high-level nuclear  
77 waste and, in particular, the utilization of plutonium and other actinides (Aoto et al., 2014). As recent  
78 practical steps, in February 2021 the BN-800 sodium-cooled fast reactor unit at the Beloyarsk nuclear

79 power plant was connected to the grid, operating solely with uranium-plutonium fuel (BN-800, 2021) and,  
80 in December 2021, the world's first high-temperature pebble-bed Generation IV reactor was launched at  
81 the Shidaowan nuclear power plant (CNNC, 2021).

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

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

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

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

122 An even greater challenge is associated with the effort to design an advanced fission or a fusion power  
123 plant, where the predictive assessment of operating conditions and reliability of reactor components  
124 necessarily requires the development and application of multiscale multi-physics computer simulations  
125 (Eyre and Matthews, 1993; Gaston et al., 2009, 2015), including models for the effects of neutron irradiation  
126 on materials (Cui et al., 2018; Mason et al., 2021; Reali et al., 2022). The coupling of models for neutron  
127 transport and thermo-hydraulics, and the verification, validation and uncertainty quantification in the  
128 context of LWR design and safety analysis were extensively reviewed in (Ivanov and Avramova, 2007;  
129 Avramova and Ivanov, 2010; Avramova et al., 2021).

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

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

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

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

## CONFLICT OF INTEREST STATEMENT

155 The author declares that the research was conducted in the absence of any commercial or financial  
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