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Review Article

Advancing Nuclear Power: Strategic Public Outreach and Technological Challenges for Sustainable Energy Futures

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Abstract

The present study examines the inadequacy of the nuclear technologies sector's public outreach strategy, which is largely dependent on the voluntary efforts of professionals employing the deficit model of communication. This approach is characterized by a one-way transfer of information and lacks a structured framework to engage the public effectively. Our analysis also highlights the critical role of material qualification in nuclear reactor facilities, as exemplified by the recent inclusion of Alloy 617 in the ASME code—the first high-temperature material certified for commercial nuclear reactor usage in the United States since the 1990s. The stagnation in the introduction of new materials has been identified as a potential bottleneck in the advancement of fission and fusion reactor technologies. Furthermore, the paper discusses the significant contribution of nuclear power to climate change mitigation, as endorsed by the IEA, which emphasizes its role in reducing CO2 emissions by replacing fossil fuel-based power plants. We also underscore the anticipated challenges associated with the expansion of nuclear power. These encompass a wide array of engineering and technological issues, including the manufacture of reactor components, fuel fabrication and extraction, development of cooling and heat transfer systems, scheduling of reactor assembly, establishment of hot cell and waste processing facilities, as well as advancements in maintenance and operational technologies for long-term reliability. The study calls for a renewed focus on strategic public engagement and a comprehensive approach to address the multifaceted engineering and technological challenges ahead for the nuclear power industry.

Keywords: *Nuclear Outreach; Material Qualification; Climate Mitigation; Nuclear Engineering*

Introduction

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. Fusion technology presents a range of scientific and engineering challenges that need to be addressed to enable the construction of a fusion power plant [1][2]. 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, 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 [3].

Similarly, the need to improve current designs and reactor components to extend reactor lifetimes may require deeper understanding of the behavior of nuclear materials under extreme conditions [4] higher temperatures than experienced with current light water reactors, 2) corrosion with liquid salts and liquid metals, and 3) high radiation fields (neutron, ion, and gamma/beta radiation fields). Materials that need to be licensed for use in the nuclear fuel cycle from reactor operation to long-term geologic disposal undergo unparalleled scrutiny. How can this process be sped up without jeopardizing future operational safety? Modern computational predictive tools could help to accelerate development and qualification of advanced materials [5]. However, this may not necessarily negate the requirement for extensive long-term testing of material properties to satisfy regulatory requirements. In this article, as well as discussing the role of ion irradiation studies for nuclear materials research, the potential opportunities for in-situ liquid/gas cell electron microscopy (LC-EM) and Cryo-Electron Microscopy (CryoEM) will be discussed [6].

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Ion irradiation in the transmission electron microscope (TEM) has been an important method for testing radiation damage in materials for nuclear applications, including nuclear waste forms and nuclear reactor components. Two other microscopy-based techniques, in-situ liquid/gas cell electron microscopy (LC-EM) and Cryo-Electron Microscopy (CryoEM) are currently being used in several areas in materials research, including, catalysis research, battery development, and geochemistry [7].

Nuclear materials, whether in a nuclear reactor or disposed thousands of meters underground in a geologic repository, are subject to internal atomic displacement damage and the interaction of radiolytic species at the material's interface. Developing the tools toexperiment in this area can be a major challenge. Working with fully radioactive materials can also be expensive and hazardous. The radiolytic field can induce very complex chemical reactions in contacting gases or liquids [8].

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 [9]. 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 [10]. 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 [11].

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 [12].

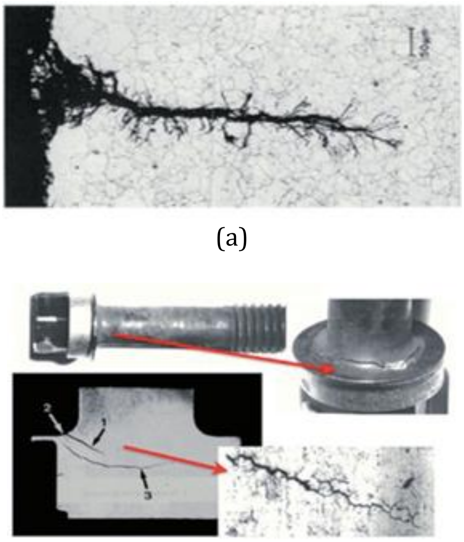
The less well established nuclear power generating options presently attracting interest are the Small Modular Reactors (SMR) [13], Fast Reactors (FRs), especially the sodium- cooled FRs that have been developed and operated since the 1970s, and the high-temperature gas-cooled reactors that could drive hydrogen production or water desalination [14]. 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. A sodium-cooled fast reactor system, a front-runner among the Generation IV reactors, 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 [15]. 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 [16] and, in December 2021, the world's first high-temperature pebble-bed Generation IV reactor was launched at the Shidaowan nuclear power plant [17][18].

A number of major fusion engineering challenges have been already addressed in connection with the design and construction of ITER 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 andaddress 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 [19] [20].

Challenges for materials in nuclear power systems

Nuclear reactors present a harsh environment for component service regardless of the type of reactor. Components within a reactor core must tolerate exposure to the coolant (high temperature water, liquid metals, gas, or liquid salts), stress, vibration, an intense field of high- energy neutrons, or gradients in temperature. Degradation of materials in this environment can lead to reduced performance, and in some cases, sudden failure [21].

Materials degradation in a nuclear power plant is extremely complex due to the various materials, environmental conditions, and stress states. For example, in a modern light water reactor, there are over 25 different metal alloys within the primary and secondary systems, additional materials exist in concrete, the containment vessel, instrumentation and control equipment, cabling, buried piping, and other (a)



(a)

(B)

Fig. 1 Examples of stress-corrosion cracking in LWR power plants. (a) Primary water stress corrosion cracking in steam-generator tubing and (b) irradiation-assisted stress corrosion cracking in a PWR baffle bolt.

Support facilities

Dominant forms of degradation may vary greatly between different systems, structures, and components in the reactor and can have an important role in the safe and efficient operation of a nuclear power plant. When this diverse set of materials is placed in the reactor environment, over an extended lifetime, accurately estimating the changing material behaviors and service lifetimes becomes complicated [22-25].

Today's fleet of power-producing light water reactors faces a very diverse set of material challenges. For example, core internal structures and supports are subjected to both coolant chemistry and irradiation effects. These stainless-steel structures may experience irradiation- induced hardening, radiation-induced segregation and changes to the microstructure. In addition, these factors may lead to susceptibility to irradiation-assisted stress corrosion cracking as shown for a baffle bolt in Fig. 1.

The reactor pressure vessel, a low-alloy steel component, also experiences radiation-induced changes and can be susceptible to embrittlement. The last few decades have seen remarkable progress in developing a mechanistic understanding of irradiation embrittlement7. This understanding has been exploited in formulating robust, physically-based and statistically-calibrated models of Charpy V-notch (CVN)-indexed transition temperature shifts. The progress notwithstanding, however, there are still significant technical issues that need to be addressed to reduce the uncertainties in regulatory application [25-28].

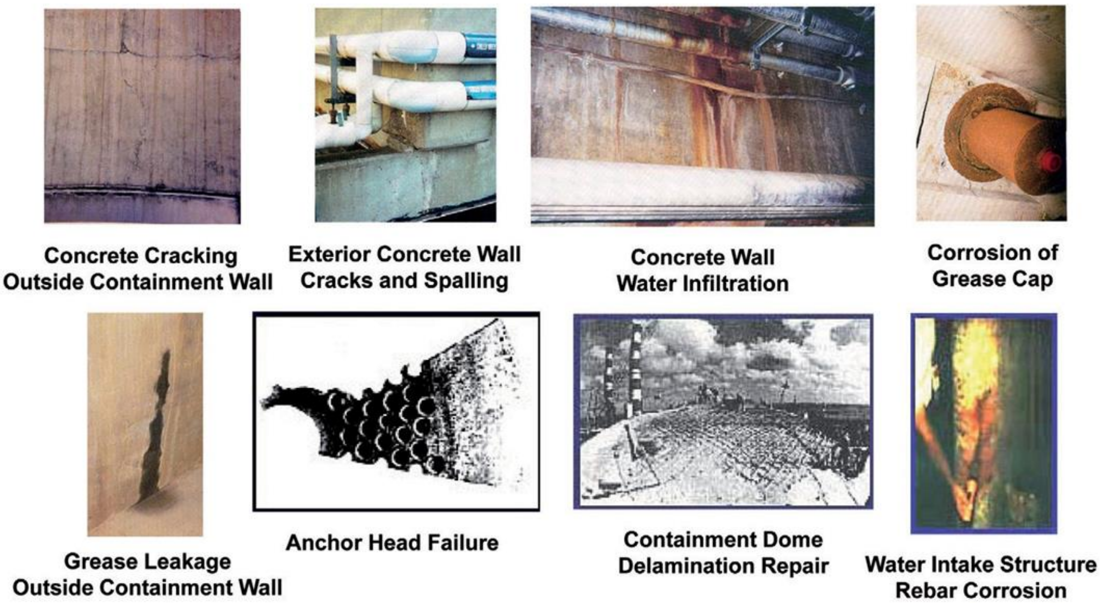


Figure 2 Examples of degradation in concrete structures. Courtesy of D. Naus

In general, concrete structures can also suffer undesirable changes with time because of improper specifications, a violation of specifications, or adverse performance of its cement paste matrix or aggregate constituents under environmental influences (e.g., physical or chemical attack) [29]. Some examples are shown in Fig. 2.

Low-dose radiation

The Linear-No-Threshold (LNT) model is based on high dose rate nuclear weapons data. Its application to nuclear reactor, medical, and irradiation applications is tenuous at best. New evidence in radiation and chemical toxicity fields is suggesting that LNT models are likely overly conservative, and the way in which they are used makes this conservatism inordinately expensive. While LNT is very straightforward to regulate, scientific evidence from the past several decades has indicated that low doses of radiation do not pose risk of cancer in a linear fashion, as is well-established among higher doses of radiation.

Today, the principle of As Low As Reasonably Achievable (ALARA) has in many cases lost the “reasonable” aspect, as nuclear power plants micromanage every milliroentgen (mR) of worker dose in order to meet metrics of dose reduction. Unnecessary fear of low doses of radiation has adversely impacted safety and enabled cumulative costs to build up within the U.S. nuclear energy industry such that building and maintaining plants is now overly cumbersome and expensive.

If the LNT model can be replaced with a modern, scientifically defensible model, underpinned by the latest microbiology research methods (genomics, proteomics, metabolomics, etc.), we can achieve both higher levels of safety while reducing unnecessary operations and waste disposal costs. One approach may be to establish a generally-accepted common measure of risk and a de minimis “threshold of regulatory concern,” socialized, and incorporated into relevant standards and regulation. Ultimately, this effort could enable broader, more cost-effective applications of nuclear technologies, which in turn would provide significant additional benefits in cleaner air, less carbon, and more lives saved from deadly diseases.

Fuel cycle

Addressing nuclear waste disposal and closing the nuclear fuel cycle would have many significant public benefits. It must be commensurate with the design of any emerging commercial nuclear products. Reducing the stockpiles of used nuclear fuel and excess stocks of highly- enriched uranium would significantly reduce the worldwide potential for proliferation of nuclear materials. The costs and maintenance of large independent spent fuel storage facilities would be greatly minimized, saving billions of dollars in waste storage and associated security costs. Additionally, it would include streamlined government regulations and permit expedited regulatory reviews, certification, and licensing for advanced reactors. Furthermore, it would enable enhanced public support for nuclear technologies and increased governmental funding for the development of advanced high- level waste-burning reactors.

Adoption of an advanced reactor-based nuclear waste disposal solution through closing the nuclear fuel cycle would enable advanced reactors to burn remaining inventories of used nuclear fuel that are currently stored at commercial and government nuclear facilities to produce significant amounts of electricity. Nuclear waste would be minimized, eliminating the need for large waste disposal facilities. Concepts, in addition to reactor solutions, would also be possible and developed, such as innovative and safe approaches utilizing Accelerator Driven Systems. These systems remove the long- term radiotoxicity of spent fuel, generate energy to recover its cost, eliminate the need for a large geological repository, and avoid the use of fuel reprocessing steps.

The current approach to the U.S. nuclear fuel cycle was formulated for reasons that are less convincing to many than they may have seemed generations ago. This has left the nuclear industry highly vulnerable to a stalled nuclear waste disposal pathway.

Rejuvenate infrastructure

Developing new technologies and their use in nuclear applications is an expensive proposition. Due to the high level of quality and reliability required for nuclear applications, navigating the complex path from development to implementation and profitable production can be a daunting and cost prohibitive process. Ensuring that there is clear guidance for new and existing suppliers will lead to competitive and cost-effective options available in nuclear technologies markets. In addition, having reliable, consistent guidance will assist regulators in quickly processing new applications. Developing the national assets of research and test facilities, be they government-operated or commercial, would provide a consistent basis for testing and approving new technologies. This applies not only to new technologies, but also to the development of replacement equipment needed for older systems.

Advanced materials

Advanced fission and fusion reactor designs offer many potential benefits, but will require new materials to be optimized. These advanced reactors have unique challenges that call for materials to resist corrosion when in prolonged contact with liquid salts or liquid metals, remain strong at elevated temperatures in a neutron field, maintain structural integrity when exposed to high fluxes of light ions and high heat flux, resist reaction in a loss of coolant event, and more.

Materials must be developed and qualified for each of these areas so that they can be implemented in new reactors. Materials issues lie at the heart of many of the technology issues that need to be solved. Without advanced materials, adequately qualified so that they can be used in engineering designs, we will never have a viable fusion or advanced fission power plant. This is a multi-faceted challenge that benefits not only nuclear energy research, but has applications for many other industries.

The current development and qualification timeline is long, especially due to limited experimental facilities and capabilities for in-reactor material irradiation testing. Significant scientific advances over the past few decades have enabled us to improve our understanding of irradiation effects on materials, including predictive capabilities. As such, we believe we can utilize these advancements to accelerate the materials qualification timeline, effectively reducing that barrier against deployment of future reactor technologies. Realizing this goal will include smart use of advanced modeling approaches, the establishment of experimental facilities and data generation for validation analysis (especially for advanced reactors), and reconsideration or modification of existing requirements for in-reactor material irradiation testing.

Simulation/experimentation

In the past half century, the nuclear energy industry and regulatory agency approach to nuclear system design and licensing has relied significantly on experimental testing. This conventional paradigm embraces conservative design principles and has ensured nuclear safety, but at the cost of extensive experiments required by the current licensing process to validate modeling and simulation tools currently in use for core design. Additionally, the lengthy and complex software quality assurance process required by the licensing authority prevents many from using newly- available models or tools, thus further delaying the use of newsimulation tools that are closer to a true predictive capability. These two issues combined deter licensing authorities from trusting the predictive capabilities of software and increases the reliance on new experiments.

The challenge thus becomes to develop and improve versatile predictive simulation capabilities that can easily integrate new models without a lengthy re-qualification process, while designing and developing a set of broad, challenging, and well-instrumented experiments that can clearly demonstrate the predictive capability of the new simulation tools and identify the areas in which the tools need improvement. Significant computational challenges exist in quantifying the impact of uncertainties on nuclear reactor performance in a multiphysics context.

Knowledge transfer

The nuclear workforce is aging, and the current university Nuclear Engineering curriculum needs to be updated. The average age of nuclear scientists and engineers in the nuclear energy industry, national laboratories, and universities is over 50. These professionals have a wealth of knowledge that is not necessarily written in books. As these workers leave the workforce, much of that knowledge is being lost.

Effective means to transfer that knowledge to the newest group of scientists and engineers needs to be developed and implemented. Additionally, the Nuclear Engineering curriculum in U.S. universities stands essentially unchanged over the past 20-plus years. With the advent of new reactor designs and the challenges within materials science to meet the needs of these new designs, the curriculum structure must be reviewed and updated to better meet the needs of industry, suppliers, and research organizations. Inclusion of courses in advanced reactor design, small reactor design and operation, and materials science may need to be included. If we do not know our history, we are doomed to repeat our predecessors' mistakes.

Author contributions

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

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