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# Editorial: Nuclear material for current and future reactor design

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Editorial on the Research Topic
Nuclear material for current and future reactor design

Nuclear energy stands as a zero-emission clean energy solution renowned for its ability to generate vast quantities of carbon-free power while utilizing minimal land space compared to other environmentally friendly energy sources. The effective and economical operation of nuclear power systems hinges significantly on the performance of the fuel and structural materials employed. Over the operational lifespan, typically spanning several decades, these materials endure extreme conditions, including high temperatures, intense radiation exposure, corrosive environments, and damage from fission products released during nuclear reactions.

The properties of nuclear fuel can undergo substantial changes influenced by factors such as fuel composition, irradiation-induced phase alterations, interactions with various transmutation products, chemical reactions between fuel and cladding materials, and mechanical behaviors. Similarly, structural materials face comparable challenges stemming from the intricate conditions of irradiation, encompassing exposure to corrosive environments that extend beyond conventional water-based systems to include molten salt environments.

Key challenges within the realm of nuclear materials encompass issues related to microstructural and microchemical alterations, as well as changes in physical properties arising from irradiation and corrosion. These challenges are intricately linked to various factors, including the generation and evolution of defects, the mobility, and precipitation of solid, volatile, and gaseous fission products, correlations between structure and property, degradation of mechanical properties and structural integrity, and radiation-induced phase transitions.

Efforts to understand and mitigate these challenges are central to ongoing research endeavors. Advanced characterization techniques, coupled with modeling approaches, play a pivotal role in elucidating radiation effects on materials at mesoscale lengths. Utilizing tools such as laboratory ion beam accelerators, research and test reactors, and commercial nuclear power reactors, researchers aim to unravel the response of materials under irradiation. Computational studies spanning multiple scales, from atomistic to continuum, are indispensable for comprehending and predicting material evolution.

However, nuclear materials research poses significant hurdles, including prolonged lead times and substantial costs incurred over decades. To expedite innovation and foster the development of novel materials, there is a growing imperative for high-throughput studies.

In this series of articles, Ortner from the National Nuclear Laboratory in the United Kingdom offers a comprehensive analysis of the crucial role played by structural materials in the design of nuclear power plants (NPPs) (Ortner). The review explores the challenges and changing perspectives surrounding material selection for NPPs, spanning historical, current, and future designs, with a focus on the necessity for materials development to tackle unique challenges specific to nuclear plants.

NPPs demand materials that can withstand extreme conditions, necessitating the development of novel materials for Generation IV designs. Challenges include achieving stability, ductility, toughness, and resistance to degradation mechanisms. Advanced manufacturing processes and welding techniques are being employed to enhance material properties and reliability in NPP operation.

The review emphasizes the importance of materials selection in ensuring efficiency, safety, and structural integrity in NPP designs. It delves into the exploration of materials such as SiC composites, Zr alloys, and tungsten for NPP components, backed by global experimental and modeling efforts to guarantee component reliability and safety. Moreover, the review discusses the challenges and risks associated with materials development, highlighting the necessity for extensive experimental campaigns and modeling techniques to support engineering decisions and mitigate risks associated with data extrapolation in Generation IV programs.

In summary, the review offers valuable insights into the evolving landscape of structural material requirements for NPPs, underscoring the significance of materials development to meet the demands of current and future NPP designs. Standardization of practices and ongoing research in materials science are pivotal in ensuring the reliability, safety, and efficiency of nuclear power generation.

The context of the current nuclear material study includes two notable contributions. One of these contributions offers insights into the importance of post-irradiation annealing of neutron-irradiated reactor pressure vessel (RPV) steels, representing a significant frontier in both technical and scientific exploration.

At the forefront of this pursuit is Small-Angle Neutron Scattering (SANS), a technique renowned for its ability to detect nanometer-sized clusters of solute atoms induced by irradiation. In a recent investigation, SANS has played a crucial role in elucidating the distribution of clusters within irradiated samples of VVER-1000 welds, providing insights into their gradual dissolution during post-irradiation annealing (Ulbricht et al.).

The results highlight the prevalence of Mn-Ni-Si-rich clusters, with radii smaller than 2 nm, as the primary source of both scattering and hardening. Notably, annealing treatments showed significant partial recovery at 350°C and near-complete restoration at 475°C, offering promising avenues for mitigating irradiation-induced embrittlement, a phenomenon that poses a threat to the long-term integrity of reactor pressure vessels (RPVs) and, consequently, the operation of entire reactor units.

Understanding post-irradiation annealing behavior is not only crucial for immediate safety concerns but also holds the key to unraveling the thermal stability of various irradiation-induced nanostructures, thus guiding the optimization of annealing protocols. Such insights, combined with computational simulations, facilitate tailored annealing strategies aimed at prolonging the operational lifespan of nuclear power plants.

While various methods with nanostructure sensitivity, such as Transmission Electron Microscopy (TEM) and Atom Probe Tomography (APT), provide valuable perspectives, SANS stands out as a pivotal tool due to its macroscopically representative and statistically reliable assessment of cluster characteristics.

This study, focusing on a low-Cu VVER-1000 weld material, exemplifies the effectiveness of systematic investigations into post-irradiation annealing. By elucidating the annealing kinetics and linking them with mechanical properties, it not only advances our understanding of nanostructure evolution but also offers insights into the comparative annealing behaviors across different RPV materials.

In the pursuit of safer and more sustainable nuclear energy, the combination of advanced characterization techniques and rigorous experimental studies heralds a promising era of innovation and optimization in post-irradiation annealing strategies.

Another contribution delves into the ongoing effort to develop an Accident Tolerant Fuel (ATF) near-term concept for Light Water Reactors (LWRs). Li et al. review the performance and failure mechanisms of chromium-coated zirconium in nuclear engineering applications (Li et al.). The research examines the behavior of the coating under various conditions, identifying stress concentration at crack tips as a primary factor leading to the failure of Cr-coated samples. Two distinct failure modes are observed: the plastic zone reaching the interface and the formation of cracks that create a coolant-substrate channel. The thickness of the coating emerges as a critical determinant of the critical crack length and the promotion of crack propagation.

Moreover, neutron and ion irradiation investigations uncover notable effects on grain growth, void formation, and the emergence of dislocation rings within the chromium coating. The coatings' resistance to oxidation and embrittlement mechanisms undergo thorough scrutiny. Computational simulations suggest a marginal impact of coating thickness on the material's balloon-burst behavior.

Framatome's experimental trials demonstrate the superior wear resistance of Cr-coated samples over uncoated counterparts across diverse wear conditions. The outcomes highlight the enhanced performance of chromium-coated samples in wear resistance assessments, indicating their potential to bolster the longevity and dependability of nuclear engineering components. Overall, this review offers valuable insights into the behavior of chromium-coated zirconium, stressing the significance of coating thickness and material properties in dictating the performance and failure mechanisms of these coatings in nuclear settings.

Lastly, the final contribution to this research domain addresses polymer materials and their utilization, as well as degradation phenomena in nuclear reactor environments due to gamma irradiation. Polymeric components play a pivotal role in safety-related electronic cables in both light water reactors and advanced reactor systems. The study concentrates on qualification initiatives aimed at unraveling the kinetics of polymer degradation to devise predictive models for assessing service life (Chen et al.). By scrutinizing existing qualification standards, degradation mechanisms, and kinetic models, the research advocates for a mechanistic-driven approach to augment predictability in the qualification of polymeric components.

Degradation mechanisms entail thermal-radial oxidative processes that influence the mechanical properties of polymers. Regulatory protocols govern safety-critical cables used in nuclear power installations, underscoring the necessity of comprehending degradation processes. Accelerated testing methodologies simulate degradation under diverse conditions, enabling the anticipation of degradation patterns through kinetic models. These models incorporate dose-rate effects and chemical suppression to offer insights into the degradation trajectory.

Advanced modeling methodologies and characterization techniques are employed to refine the understanding of degradation mechanisms and enhance the reliability of qualification procedures. By integrating these advancements, the research strives to transition from traditional accelerated aging approaches to mechanistic-based prognostications. This evolution in qualification strategies is advantageous not only for safety-critical cables but also for other nuclear material endeavors, contributing to an overall enhancement in nuclear safety and reliability.

In conclusion, the article underscores the importance of studying polymer degradation in nuclear settings and emphasizes the necessity of developing precise predictive models to ensure the long-term performance and safety of polymeric components in nuclear power systems. The findings articulated in this study furnish valuable insights into the qualification and modeling of radiation-induced polymer degradation, laying the groundwork for augmented safety and reliability in nuclear power applications.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note