Foreword

Special Issue Featuring Selected Papers from the 2024 International Congress on Advances in Nuclear Power Plants (ICAPP 2024)

Guest Editors

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This special issue of *Nuclear Technology* contains selected papers from the 2024 International Congress on Advances in Nuclear Power Plants (ICAPP 2024). The contributions assembled here represent a snapshot of a rapidly evolving field: the deployment, operation, and long-term stewardship of nuclear power plants in an era defined by energy security and accelerating technological change.

Nuclear energy already provides a significant share of the world's directly dispatchable electricity, and many recent analyses suggest that global nuclear capacity will need to scale substantially, potentially doubling, tripling, or quadrupling by mid-century. In that context, ICAPP 2024 and this special issue highlight how the nuclear community is rethinking plant design, economics, safety, operations, and integration with broader energy systems.

I. THE ICAPP MEETING SERIES AND ICAPP 2024

Since its inception in 2002 as an embedded topical meeting of the American Nuclear Society (ANS) Annual Conference, the International Congress on Advances in Nuclear Power Plants (ICAPP) has become a leading forum for researchers, industry practitioners, regulators, and policymakers to discuss advances in nuclear power plant technology. Held on a regular cycle in North America, Europe, and Asia, ICAPP brings together perspectives from operating utilities, vendors, laboratories, universities, and start-ups and provides an archival record of progress through its peer-reviewed proceedings.

ICAPP 2024 was held June 16–19, 2024, at the Mandalay Bay Resort and Casino in Las Vegas, Nevada, as an international embedded topical meeting within the 2024 ANS Annual Conference. Under the leadership of honorary chairs Fiona Rayment and Tadashi Narabayashi, general chairs Travis W. Knight and Jacopo Buongiorno, and technical program chairs Piyush Sabharwall and Neal Mann, the congress featured two dedicated plenary sessions—on unlocking the potential of the nuclear industry for a secure global energy paradigm and on decarbonization as a driver for a nuclear energy comeback—alongside a rich program of technical sessions and panel discussions.

The technical program was organized into 12 tracks covering nuclear power plants; reactors for heat and combined heat and power; portable and propulsion reactors; nonenergy applications; reactor physics; thermal hydraulics; fuels, materials, and structures; plant safety, regulation, and licensing; markets and financing; innovative manufacturing and construction; operation, performance, and reliability management; and fuel cycle and waste management. Presentations within these tracks spanned the full technology life cycle, from conceptual design and analysis through experimental validation, licensing strategy, and early deployment experience.

II. TECHNICAL DISCUSSIONS AT ICAPP 2024

A recurring theme in the technical discussions at ICAPP 2024 was the maturation of advanced reactor concepts and their applications beyond traditional baseload electricity. Several sessions examined high-temperature gas-cooled, sodium-cooled, molten salt, and microreactor designs aimed at supplying flexible power, industrial process heat, district heating, hydrogen and ammonia production, and off-grid or transportable

applications. Coupled neutronic–thermal-hydraulic modeling, seismic and structural analysis, and integrated energy system optimization all featured prominently as tools to turn these concepts into licensable, financeable projects.

Another strong current was the digital transformation of nuclear operations. Papers addressed digital twins, online condition monitoring, probabilistic risk assessment, and advanced control, and the application of machine learning and artificial intelligence to anomaly detection, remaining useful life estimation, and autonomous or remote operation. These developments reflect a shift from traditional periodic inspection and conservative margins toward data-rich, risk-informed decision-making that can improve reliability while containing operating and maintenance costs.

Throughout the conference, safety remained a central concern, from severe accident analysis and source term estimation to seismic isolation strategies and the qualification of new materials and components. At the same time, tracks on markets and financing, innovative manufacturing, and fuel cycle and waste management underscored that the success of nuclear projects hinges not only on technical performance but also on cost competitiveness, robust supply chains, effective financing frameworks, and credible approaches to long-term waste disposition. The interdisciplinary flavor of ICAPP 2024, i.e., linking engineering detail with economics, policy, and societal expectations, is reflected in the papers selected for this special issue.

III. CHALLENGES AND OPPORTUNITIES FOR NUCLEAR ENERGY

The global context in which ICAPP 2024 took place is both challenging and promising for nuclear energy. Many countries have adopted net-zero greenhouse gas targets, and recent analyses by international organizations emphasize that maintaining affordable and reliable power systems consistent with those targets is significantly easier if nuclear power plays an expanded role. At the same time, political initiatives calling for a substantial increase in worldwide nuclear capacity by mid-century signal renewed interest in nuclear energy as a cornerstone of energy security.

Delivering on that ambition, however, will require overcoming substantial obstacles. High upfront capital costs, long construction schedules, and financing risk continue to challenge large-scale nuclear projects. For small modular and other advanced reactors, attention has turned to supply-chain readiness, reevaluation of codes and standards, and manufacturing innovation as key levers for cost and schedule certainty. Regulatory frameworks designed around large conventional reactors must adapt to accommodate novel designs and deployment models and new uses of nuclear technology, while preserving the sector's strong safety culture and public confidence.

On the research and operations side, the community faces the dual task of extending the life and performance of the existing fleet while bringing new technologies to market. This entails continued progress in fuels and materials under demanding conditions, more accurate and computationally efficient modeling and simulation, improved methods for risk-informed decision-making, and the adoption of digital technologies—including automation, robotics, and advanced data analytics—without compromising cybersecurity, human factors, or regulatory expectations. It also calls for creative approaches to workforce development and knowledge transfer as demographics evolve.

ICAPP 2024 directly engaged with these issues by providing a venue where detailed technical work was situated within the broader questions of deployment, economics, and policy. The papers in this special issue exemplify that blend: Collectively, they address advanced coolants and heat transfer systems, process heat integration, passive safety features, seismic risk optimization, robotics, digital twins, and innovative approaches to operations and maintenance. Individually and together, they demonstrate how targeted research and development can translate into practical tools and design insights that will help the nuclear sector contribute to a net-zero, secure energy system.

IV. OVERVIEW OF THE SELECTED PAPERS

This special issue includes 11 papers selected from ICAPP 2024 and subsequently extended and peer reviewed for publication in *Nuclear Technology*. They illustrate the diversity of topics presented at the congress while maintaining a clear focus on technologies and methods with the potential to impact the design and operation of current and future nuclear power plants.

Vasquez and coauthors report an experimental study of how gamma irradiation modifies the chemical and physical characteristics of a candidate organic coolant for advanced reactors. By quantifying radiation-induced changes in key thermophysical and chemical properties, their work provides an early assessment of the viability of

organic coolants in high-flux environments and helps identify data needs for future qualification efforts.

Ajay and colleagues perform a technoeconomic assessment of integrating advanced nuclear reactors as providers of industrial process heat, illustrated using an ammonia-production case based on biomass feedstocks and nuclear microreactors. By combining process modeling with cost analysis, they explore when nuclear-supplied heat can be competitive and highlight the importance of matching reactor design, heat delivery systems, and industrial demand profiles.

Kimura and coauthors examine the kinetic behavior of the IGEM passive reactivity control device in the MoveluX core concept, supported by measurements and observations of adhered liquid metal. Their analysis clarifies how this passive system responds during transients and contributes to overall reactivity control, informing the design and safety evaluation of reactors that rely on such devices.

Celik and Bang analyze the influence of helium gaps on the thermal performance of two compact heat transfer components: a heat pipe and an axial flow–type heat exchanger. Their results clarify how gap configuration affects effective heat transfer characteristics and provide guidance for the thermal design of high-temperature reactor systems that employ similar components.

Moon, Jang, and Kim focus on seismic risk in nuclear power plants, proposing a methodology to identify key components and optimize risk reduction measures to improve overall seismic performance. By integrating risk metrics with structural performance considerations, they offer a framework for prioritizing where design enhancements or protections yield the greatest safety benefit for both existing plants and new builds.

Patterson and coauthors present a framework for training autonomous robotic systems for nuclear applications using machine learning methods in simulated realities. Leveraging virtual environments to develop and test task-specific policies before deployment, they illustrate how robotics and artificial intelligence can reduce worker exposure in hazardous areas and expand the range of inspection and maintenance tasks that can be automated.

Mandelli and Sowder introduce a "build-to-replace" strategy aimed at reducing operation and maintenance costs in advanced reactors. The concept emphasizes designing plants such that replacing standardized modules, rather than repairing them in situ, becomes the preferred maintenance approach, with the potential to simplify outage planning, shorten downtime, and support more predictable long-term cost structures.

Kim, Cetiner, and Bucci develop an inverse-problem methodology for estimating operating conditions and associated uncertainties in a forced-convection thermal-hydraulic system using measured data. Such approaches can support experimental analysis and plant diagnostics by reconstructing internal states that are difficult to measure directly while quantifying the confidence in those reconstructions.

Chen and colleagues discuss technologies that enable the development of digital twins for online condition monitoring of nuclear power plant components. Their paper articulates functional requirements and an overall architecture for combining physics-based models, sensor data, and data-driven analytics into virtual representations of key systems that can support diagnostics, prognostics, and risk-informed maintenance decisions.

Shishido and Hashizume explore the concept of using a fusion reactor as a dedicated transmutation system for minor actinides and selected fission products. Through a conceptual analysis of candidate blanket configurations and operating modes, they discuss how such a system could reduce long-lived radiotoxic inventories and complement other strategies for fuel cycle optimization and waste management.

Che, Burak, and Sun explore performance of molten salt pump shaft seal candidate designs under static and dynamic conditions. Initial simulation results led to testing of design and boundary condition modifications to mitigate the effects of thermal stress caused by thermal expansion.

Taken together, these 11 papers illustrate a coherent narrative about the future of nuclear power plants. Several contributions, i.e., those on organic coolants, passive reactivity control, helium-gap heat transfer performance, seismic risk optimization, fusion-based transmutation, and molten salt pumps, address fundamental questions about plant and fuel cycle technology that underpin the safety and performance of advanced systems. Their results feed directly into design choices for next-generation reactors and supporting infrastructure.

Another subset of papers focuses on the economic and systems context in which plants will operate. The techno-economic analysis of process heat integration articulates how advanced reactors can decarbonize energy-intensive industries, while the build-to-replace strategy targets one of the most important cost drivers for existing and future nuclear plants: operation and maintenance expenditures. The inverse-problem methodology connects physics-based understanding with improved monitoring and diagnostics,

bridging the gap between experimental facilities and plant-scale applications.

Finally, the contributions on robotics and digital twins highlight the emerging digital ecosystem around nuclear power plants. Autonomous robots trained in simulated realities, coupled with high-fidelity digital twins of critical components, point toward a future in which inspection, maintenance, and operations increasingly rely on virtual prototyping, data-rich decision support, and tightly integrated human-machine collaboration. These developments are especially relevant as the industry contemplates remote and multiunit operation, microreactor fleets, and new ownership and business models.

By spanning coolants and materials, core physics, thermal hydraulics, structural and seismic performance, diagnostics, robotics, and economic analysis, the selected papers collectively demonstrate the breadth of innovation required to make advanced nuclear plants both technically compelling and commercially attractive. They also underscore the value of venues such as ICAPP in bringing together communities that might otherwise operate in disciplinary silos.

V. ABOUT THIS SPECIAL ISSUE

The papers in this collection were chosen through a two-stage process. First, they were peer reviewed and presented at ICAPP 2024. Authors of selected contributions were then invited to substantially revise and expand their work for consideration in *Nuclear Technology*. Each article in this special issue has undergone the journal's standard peer review process, ensuring that the results are documented with the rigor and clarity expected of the archival literature.

We are grateful to the authors for their responsiveness during this process and for the care they devoted to updating and extending their conference papers. We also thank the many anonymous reviewers who provided thoughtful and constructive feedback, as well as the *Nuclear Technology* editorial team for their assistance in bringing this special issue to fruition. Finally, we acknowledge the organizers of ICAPP 2024 and the ANS staff for creating a vibrant meeting that continues to catalyze innovation in nuclear power plant technology.

We hope that readers will find this special issue informative and inspiring—whether they are engaged in the design of new reactors, the operation and life extension of the current fleet, or the development of policies and business models that will shape nuclear energy's contribution to a decarbonized energy system. We look forward to future ICAPP meetings and to the continued evolution of ideas represented in these pages.

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