Foreword

Selected papers from the 24th Topical Meeting on the Technology of Fusion Energy

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The present environment for fusion energy development is one with increasing momentum. As ITER prepares for first plasma and ultimately burning plasma operations, demonstration power plants and next-step pilot plants are in early design phases around the world, and fusion enterprises continue to emerge targeting a wide range of configuration approaches. New confinement facilities have come on line, with the Wendelstein 7-X and JT-60 Super Advanced (JT-60SA). A new drive is provided by the impact of climate change and the search for ways to mitigate its continued progression. Recent fusion community and advisory committee reports in the United States have developed a consensus view that now is the time to shift from a science focus to energy development, something not seen since the 1980s.

The American Nuclear Society (ANS) Technology of Fusion Energy (TOFE) conference provides a unique venue to describe the ongoing research toward the fusion nuclear regime. Held virtually November 16–19, 2020, the TOFE 2020 conference brought nine diverse disciplines together online: superconducting magnets, nuclear analysis, tritium fuel cycle, plasma and enabling technology, plasma-facing components and high heat flux, plasma–material interactions, liquid metals, materials, and fusion safety and blankets. Special sessions were held on the fusion enterprises, both to briefly describe their activities and to answer questions about their plans and challenges. The plenary speakers opened each day with excellent overviews of wide-ranging topics: the history of the Savannah River National Laboratory (SRNL), and recent efforts in the United Kingdom to explore the opportunities to bring fusion knowledge to industrial activities and cutting-edge approaches in other technical areas back to fusion; a presentation of the Japanese DEMO research and development (R&D) on their roadmap to fusion power, and the staggering challenge of handling plasma disruptions as fusion moves to power production; and the meticulous strategy for neutronics in the European DEMO development, and the challenging and rewarding activities toward advanced manufacturing for nuclear applications in the United Kingdom. On the last day, the plenary covered the broad global activities of the International Atomic Energy Agency in fusion, the tritium R&D performed at the SRNL now and the many years of expertise acquired, and the exciting threshold of first plasma on the new advanced tokamak facility JT-60SA.

The emerging capability of high-temperature *superconducting magnets* has the potential to improve magnetically confined fusion approaches through improved fusion performance and more compact facilities. Developing new conductors, reaching higher fields, handling stresses, practical manufacturing, and understanding superconductor operational behavior continue to drive the field on the way to reliable and reproducible magnets for fusion.

Nuclear analysis is fundamental in describing the nuclear source and its impact on all components of a fusion power facility. Fusion nuclear energy development relies on the accurate computation of neutron transport and the determination of nuclear impacts over the broad range including heating, damage, transmutation and gas production, radioactive material production, decay heat and dose rate, and material activation over time, as well as radwaste disposal. Elaborate computational frameworks exist to handle the crushing load of data and analysis typical of the fusion nuclear regime. In a fusion facility, the neutron flux can vary by over 13 orders of magnitude from the harsh fusion core to the human-accessible zones, requiring extreme efforts to model systems and nuclear transport via accurate source terms over ever larger volumes. Significant efforts are required in establishing shutdown dose rates to guarantee worker and equipment safety during maintenance and inspection. Nuclear data are fundamental to accurate predictions of all nuclear impacts, requiring continuous scrutiny and validation experiments. Beyond the traditional roles of nuclear analysis in fusion reactor design, its input to materials science and fusion safety and licensing is critical to guide R&D and establish acceptable responses and environmental impacts. ITER has played an important and near-term role in pressing the fusion nuclear community to ever greater model accuracy, computational speed and fidelity, data validation, and plantwide system assessments, requiring substantial enhancement to procedures and protocols.

The *tritium fuel cycle* is a unique requirement of the deuterium-tritium (D-T) fusion energy endeavor and will lead to significant inventories of tritium within a fusion power plant. Tritium is produced in the breeding blanket and recovered to support the fuel cycle. Meanwhile, an amount of tritium 10 to 100 times larger must be circulated continuously through the plasma chamber to sustain fusion power production, with only 1% to 10% of the fuel consumed in each pass. Although these two loops attract much attention in fusion reactor design, there are many more features to the fuel cycle. The extraction of tritium from primary fluids remains an unproven technology, fueling the plasma at the rates and durations required has not been demonstrated, and tritium migration throughout the fusion core and its interactions with the associated materials remain complex and uncertain. The tritium handling for the entire plant relies on a large number of apparatuses for pumping, separation, capture, storage, and cleanup. Each of these must be designed for the anticipated load and for off-normal conditions, and advances in these technologies are required to reduce the size and cost and to enhance efficiencies wherever possible. The larger quantity of tritium in a fusion power plant demands the development of extraordinary precision and control of tritium movement, recovery, and storage, and these are the focus of ongoing activities worldwide.

Plasma and enabling technology includes many disciplines and supports several systems in a confined plasma fusion device. At TOFE 2020, structural and other multiphysics analyses were reported for lower hybrid wave launchers, along with research on a vacuum vessel for a quasi-symmetric stellarator, the ITER electron cyclotron heating transmission line, the National Spherical Torus Experiment-Upgrade (NSTX-U) poloidal coil support, and the ion cyclotron range of frequency system on ITER. ITER residual gas analysis, shear strength of the pellet for shattered pellet injector, and particulate impurity injection all address plasma–particle interactions. Inertial electrostatic confinement was reported. Plasma–material interaction experiments were described; NSTX-U center stack bakeout and assembly and advanced engineering design and manufacturing approaches were discussed. The design space exploration, and limitations to that space, of fusion nuclear facilities were also presented.

Plasma-facing components must endure fusion nuclear heating, plasma surface heating, and particle fluxes. Reports were given on helium gas impingement cooling of divertor surrogates, water cooling of swirl tape–enhanced CuCrZr monoblock designs under cyclic loading, and helium cooling of blanket first wall cooling channels. Vibration-enhanced boiling heat transfer and thermal performance of tungsten-armored graphitic foam were presented, and both tungsten impurity sourcing and tungsten emissivity as a diagnostic were discussed.

Plasma–material interactions are a critical feasibility challenge for fusion development, and significant R&D is required to establish materials and component designs that will withstand the harsh plasma loading. Presentations were given describing the Material Plasma Exposure eXperiment (MPEX) linear plasma project, including motivation, project steps, and the use of proto-MPEX to examine several design approaches. The design of the helicon plasma source window and the steady-state cooling and thermomechanics of the target were reported. The initial design for a hydrogen loop to explore material behavior for nuclear thermal propulsion applications was discussed.

Liquid metals have long been considered for use in fusion energy systems as tritium breeders and coolants. Since these fluids are generally good electrical conductors, moving them through strong magnetic fields requires both special simulation techniques and engineering solutions for their sustainment. Extensive experiments on PbLi and Li were reported in support of breeding blankets, liquid metal plasma-facing components, and materials testing facilities. Simulation activities continue worldwide, developing, benchmarking, and validating several computational fluid dynamics treatments that include magnetohydrodynamics phenomena.

The application to fusion blankets includes energy and mass transport and can also include electromagnetic and centrifugal flow control. Creating a complete liquid metal loop for fusion requires additional development in tritium extraction, corrosion, heat exchange, and cleanup, as well as system-level assessments associated with multiple blanket modules fed by a single manifolding system. Significant progress has been made in the past decade for liquid metals in fusion, and comprehensive predictions approaching the parameters of fusion are approaching.

A fusion facility will require many different *materials* for a wide range of applications, including breeding blankets, divertors and other plasma-facing components, radio-frequency launchers, structures, nuclear shields, magnets, and fuel cycle apparatuses. Corrosion research was reported for PbLi liquid metal and FLiNaK molten salt. The behavior of a ceramic breeder material was presented, noting the complex lithium and tritium movement through the material under irradiation. Tungsten oxidation experiments, joining and manufacturing, irradiation impact on electrical and thermal conductivity, and damage under helium bombardment were described to better understand the behavior of this potential plasma-facing material. Additive manufacturing for plasma-facing components was shown to be a ripe area for development, high-entropy alloys were shown to have potentially attractive responses to irradiation, and materials testing in a D-T neutron generator is continuing to progress toward higher neutron fluxes. Copper alloys with higher strengths and operating temperatures are being explored and have been advance-manufactured for fusion applications. Analysis describing magnetic materials utilizing vector potential elements was described. Results on the thermal stability of tritium storage material LANA.75 and Grafoil use in the NSTX-U plasma-facing component mounting were presented.

Fusion safety and blanket sessions reported a personnel protection and safety protocol for the NSTX-U utilizing U.S. Department of Energy best practices and industry standards. In addition, presentations were given on the behavior of tritium in organic plant matter (that could be consumed by humans) and its behavior in soils. A strategy for handling tritium off-site hazards similar to the U.S. Environmental Protection Agency chemical hazard strategy was proposed, and three-dimensional computational fluid dynamics simulations of a loss-of-helium-coolant accident into the vacuum vessel were performed, illustrating the complex initial behaviors that ultimately relax to agree with more global thermal-hydraulic treatments. The potential of a porous heat transfer medium for plasma heat flux on the blanket was explored. A new facility is being developed to allow integrated testing of fusion core components in a multifactor environment, including high magnetic field, fast field changes, and surface and volumetric heating at ITER test blanket module scale.

Fusion enterprise sessions were held to describe the various approaches being taken by these pioneers toward commercial fusion power production. Magnetized target fusion at General Fusion was described by Michel Laberge; projectile inertial fusion at First Light Fusion, Ltd., was described by Jamie Darling; nuclear medicine development at SHINE Medical Technologies, LLC, was described by Greg Peifer; high-power spherical tokamak fusion at Tokamak Energy was described by David Kingham; sustained spheromak fusion at CTFusion, LLC, was described by Derek Sutherland; and commercialized neutron sources at Phoenix Nuclear, LLC, were described by Ross Radel. These presentations provided technical descriptions, historical company stories, and many important insights into the challenges of starting new companies based on complex technical endeavors. A panel discussion among the enterprise speakers provided very candid and interesting interchanges covering regulatory issues, the COVID-19 pandemic, artificial intelligence, public–private partnering, and desired skills for new young scientists.

On behalf of the entire organizing committee and ANS headquarters, it is with great pleasure that we thank our colleagues around the world for participating in the ANS TOFE 2020 conference, in spite of the challenges presented by the COVID-19 situation. We look forward to seeing all of you in person at a future fusion energy conference and hearing about your latest achievements. Special thanks are given to the tireless efforts of the ANS support staff for the conference and the editorial staff for *Fusion Science and Technology.*

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