ARTIFICIAL INTELLIGENCE FOR CLIMATE CHANGE MITIGATION ROADMAP (SECOND EDITION)

CHAPTER 10:

NUCLEAR POWER

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NUCLEAR POWER

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Nuclear power provides low-carbon, dispatchable power in large quantities. It has the potential to contribute significantly to achieving the goals of the Paris Agreement.[1] At the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP28) in December 2023, 25 countries pledged to triple their nuclear power capacity by mid-century.

Meeting this pledge will be a challenge. High costs, public opposition and other factors have limited the growth of nuclear power for decades. Indeed in 2023, nuclear power output globally was two percent *below* its 2006 peak.[2] China leads the world in new nuclear power capacity but has added only 2–3 GW per year—a stark contrast with the 210 GW of new solar power capacity added in China last year.[3] Japan has reopened only 12 of the 53 reactors that were operating before the 2011 Fukushima accident.[4] New nuclear reactors recently opened in the United States for the first time in eight years.[5] Germany has closed its last reactors, and Spain may soon follow.[2,6] France—which leads the world in the percentage of nuclear power on the electric grid—has seen extensive delays and cost overruns in constructing a new reactor type (the European Pressurized Reactor) and may replace some nuclear reactors with solar and wind power.[7] Many developing countries aspire to nuclear power but lack the resources, and the political situation in many developed countries remains murky. All this taken together has resulted in the global share of primary energy that comes from nuclear sources remaining flat at about nine percent in the last few years.[2]

If nuclear power is going to make a bigger contribution to the world's growing energy needs, the industry will need to reduce the time and cost required to build new reactors and to optimize operations of legacy reactors and new models. One way to accomplish this goal is to harness technological improvements from outside the nuclear industry, such as artificial intelligence (AI).[9]

AI could raise the productivity of reactors already in service, increasing their annual hours of operation. It could reduce the amount of uranium enrichment these reactors require, cut the volume of nuclear waste they produce and assist in evaluations needed to extend their lives. AI could also cut the cost of electricity produced by new reactors by optimizing the design of their cores. Proponents are hopeful that AI could shorten the time needed to license new reactors, reduce the staffing requirements for those reactors and eliminate unnecessary radiation exposure to plant staff.

Figure 10-1. *Boiling water reactors at the Enrico Fermi Nuclear Plant in Newport, Michigan, USA.*[8]

AI could be a key part of a "faster/better/cheaper" approach.

But there are barriers to these potential contributions. One is that existing nuclear plants are largely analog and create far less data than digitized industries do. Also many nuclear databases are proprietary and may not be in a usable form. In addition, regulators are quite conservative about incorporating new tools into nuclear design and operations. (These problems are related. One reason legacy reactors in the United States do not have large databases of their performance is that the US Nuclear Regulatory Commission (NRC) has held back licensees' efforts to digitize controls.)

AI is a fast-moving technology; nuclear power is a slow-moving industry with especially slow-moving regulators. AI has just begun to demonstrate its value in operating nuclear power plants. Whether AI can ease or speed deployment of additional nuclear reactors remains unclear.

This chapter explores how AI could add value in the nuclear power sector. The chapter explores AI applications in operating reactors, advanced reactor design, nuclear waste management and the nuclear regulatory process, discusses barriers and risks and offers nine recommendations.

A. Operating reactors

AI can help improve operations in a number of ways at nuclear reactors that are already operating. The US Department of Energy's (DOE's) Idaho National Laboratory has suggested that AI can support nuclear power in the following ways:

- "Detecting process anomalies in a nuclear power plant before they develop into significant events
- Automating paperwork activities of nuclear power plant operators by applying natural language processing methods to documents that are generated daily
- Applying classical and machine learning (ML)-based image processing to automate manual and visual tasks in a plant
- Creating risk-informed predictive maintenance strategies for nuclear power plants that are based on predictive models developed to monitor an identified plant asset
- Developing intelligent operator aids to enhance the operator's ability to monitor nuclear plant systems and components
- Preventing and managing corrosion
- Creating virtual operators to run simulations so reviewers can identify human factors that affect performance"[10]

The US Electric Power Research Institute has observed growth in the deployment of sensors and other instruments at nuclear power plants. These tools provide a vast amount of information about a nuclear power plant's operational status. This growth of information about operational performance provides an opportunity to use AI tools to increase reliability and efficiency.[11]

i. Fuel management

One consulting firm (Blue Wave) has been using AI since 2016 to reduce the number of fuel assemblies needing premature replacement at boiling water reactors (BWRs). The firm also uses AI to help find sensors whose out-of-calibration readings could have led to shutdowns or reduced energy production.[12,13]

The design of BWR cores is complex due to uneven water density between the top and bottom (more of the water is steam near the top). AI may be better than humans at specifying optimum distribution of the more fissile type of uranium within the core, allowing full power operation until a refueling outage and ensuring the fuel is completely used up at the time of scheduled refueling.[13]

AI can avoid another problem: having to replace a fuel bundle early because the bundle does not have enough energy potential left to last until the next scheduled refueling. Replacing assemblies early increases the volume of nuclear waste. Blue Wave says it has saved 110 assemblies across the 16 units that use its software. (BWRs have between 300 and 800 fuel assemblies.)

Figure 10-2. *Boiling water reactor fuel bundle.*[8]

ii. Sensor and camera readings

AI can also optimize reactor operations by analyzing sensor readings. In one instance, a utility reported that its reactor was producing more and more steam and was projected to exceed its licensed limit within days. The utility proposed to insert control rods to reduce energy output. Instead, using a digital model and AI tools, Blue Wave concluded that of the 172 sensors that measured power in different spots in the core, 7 were giving inaccurate readings. (In-core sensors in a BWR have limited lifetimes.) Turning off the inaccurate sensors allowed the utility to calculate that it was operating well within its thermal limits, and the plant avoided losing production.[13]

Blue Wave sees other potential uses for AI:

- Nuclear plants make extensive use of security cameras, but human beings do not always notice what the cameras capture
- AI does not get bored and could categorize everything on the screen, sorting the images as normal or not normal and flagging the ones that need human attention

Likewise, plants use remotely controlled cameras to scrutinize reactor vessels and other components. AI could be taught to look for images on screen that merit follow-up and flag them for human operators. Both these examples are machine assistance to human decision-makers, and as such, proponents say they may avoid triggering NRC licensing requirements.[13,14] This is important because reactor owners are reluctant to make any changes that force them to go to regulators for license amendments or other rulings. In the United States, changes that require NRC approval can take a year or more and cost a licensee thousands of dollars in NRC review fees.

iii. Operator tasks and robotics

Other companies have been developing AI tools for use at nuclear power plants. NuclearN[15] provides products to automate the tasks and challenges operators typically face. The idea of automating nuclear operations and maintenance dates back to the 1980s.[16] Some labeled the "lack of intelligence" the Achilles heel of nuclear robotic technology. But today, AI is driving configuration and operation in robotics in sectors ranging from automobile manufacturing to household vacuum cleaners and from medical surgical equipment to aerial drones used in agriculture and defense. AI can enhance the functionality, versatility and precision of robots. AI-powered robots can have advanced software, computer vision and decision-making capabilities that allow them to operate more autonomously and effectively than those not powered by AI. In some nuclear facilities, AI-controlled unmanned platforms (e.g., quadrupeds, such as SPOT)[17] are already at work.

These developments are gradually being ported to the nuclear sector, with a focus on robotics first and software second. The United Kingdom's Research and Innovation agency sponsored a five-year research program at this interface.[18] The European Union's Robotics for Inspection and Maintenance project focused on nuclear facilities.[19] The Organization for Economic Cooperation and Development's Nuclear Energy Agency has an ongoing initiative focused around decommissioning,[20] while recent nuclear robotics deployments in Japan have been well documented.[21]

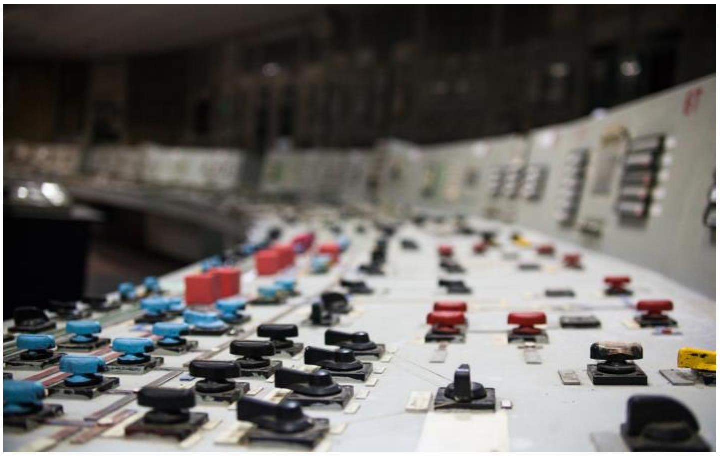

Figure 10-3. *Nuclear power plant control panel*

These initiatives and deployments encourage research into the modifications needed to adapt these technologies to nuclear requirements. Some examples of research at this interface include:

- A semi-autonomous pipe-cutting robot in radiological environments[22]
- The role of AI in remote glovebox operations in nuclear settings[23]
- AI for nuclear decommissioning projects[24]

iv. Corrosion

Material corrosion is one of the nuclear industry's great challenges. Annual costs from corrosion-related aging and degradation due to radiation exposure are significant, even for advanced metals (e.g., Zircaloy). The risks and challenges with corrosion have increased as reactors' licenses are extended, demanding longer and better performance from plants and operating systems. AI could help extend the lifetimes of reactors already operating and improve operations in reactors now being designed, saving operators cost and reducing maintenance outages (planned and unplanned).

Materials discovery presents a terrific opportunity for AI-driven improvements in nuclear power, as in other fields. (Chapter 13 of this Roadmap discusses this opportunity in depth.) This is particularly true with respect to advanced alloys used in pressure vessels, specialty welding and reactor claddings, which can be damaged by direct radiation exposure and interaction with advanced coolants (e.g., molten salts). Discovery of new alloys or optimal production of existing alloys could deliver significant improvements and would likely have applications to both reactor design and waste storage systems.

The same is true for AI applications in process and control systems. For example, using operational data from sensors and controls, AI could help detect corrosion earlier and improve maintenance cycles. (Chapter 5 presents similar applications of AI within the manufacturing industry.)

v. Life extensions

In many countries, nuclear power plants face challenges due to declining prices of electricity in wholesale markets, driven by technical improvements in competing sources of energy and subsidies for them. AI can help reactors meet this financial challenge by cutting the cost of producing electricity in a nuclear plant, by improving fuel utilization (using less and wasting less), reducing unnecessary shutdowns and making it more feasible to extend the life of a reactor.

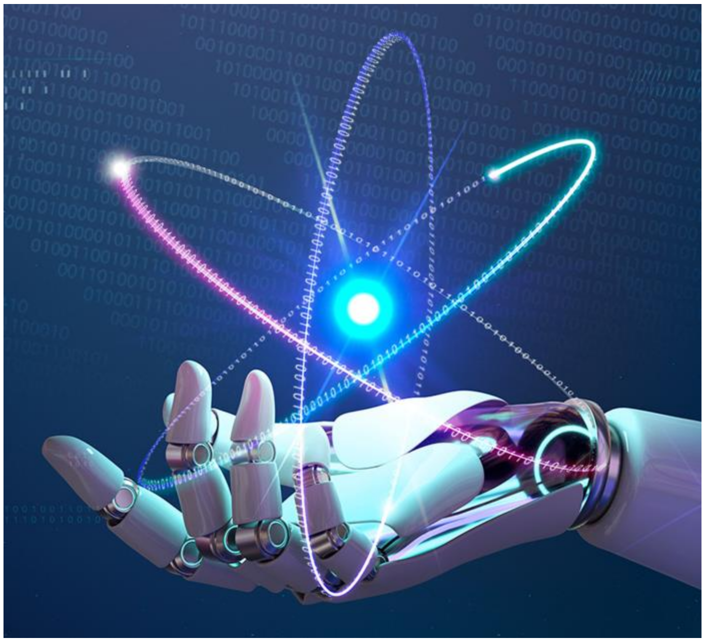

Figure 10-4. *AI can manage nuclear processes efficiently.*

Indeed at nuclear reactors that are currently operating, AI can help analyze the potential for life extension. For example, AI can help measure the extent of radiation damage to concrete—a prerequisite for life extension. The aggregates used in concrete often include quartz, and when quartz is hit by a neutron, its structure is damaged. Technicians can use a technology called x-ray computed tomography to look deep inside concrete structures and see the extent of damage. However, the images are low contrast, and the work is so tedious that the accuracy of a human analyst interpreting the images may not be high enough. Researchers at DOE's Oak Ridge National Laboratory have used AI to scan the images more accurately.[25]

ARTIFICIAL INTELLIGENCE (AI) CAN SAVE NUCLEAR FUEL

As discussed above, when operators of a US boiling water reactor (BWR) saw that sensors indicated power levels were rising beyond license limits, they thought they would have to change rod patterns within a few days to reduce energy production. However, they used AI to determine that 7 of the 92 sensors were giving inaccurate readings and that excluding them from analysis of the core would improve accuracy. They kept power at 100 percent, just below the license limit.

Engineers' initial analyses of the cores of several reactors showed that they would have to replace 104 assemblies after just 2 cycles, rather than the standard 3, but AI analysis of just how many megawatt-hours of energy each fuel assembly in a BWR had actually produced allowed operators to leave them in place for a third 2-year cycle. This reduced their costs and the volume of nuclear waste.

B. Advanced reactor design

AI can assist in designing advanced nuclear reactors.[26]

i. Thorium-Fueled Fission Reactors

Thorium is a radioactive element whose main isotope, Th-232, is four times more abundant than most uranium and about four hundred times more abundant that U-235 (used in nuclear fuel). The current favored design for thorium-fueled reactors is a molten salt-cooled reactor, in which the thorium fuel would be mixed directly with the molten salt coolant.[27] The design does not use cooling water, a distinct environmental advantage, and is believed to have a smaller risk of core damage compared to water-based nuclear reactors. Other advantages include low risk of weaponization or proliferation, high efficiency, high-temperature heat generation and reduced production of waste.[28] China has built a thorium reactor, and other nations are considering it as well.[29]

AI could potentially contribute positively to many aspects of thorium reactors. AI could optimize fuel, coolant and reactor design against multiple objectives (cost, safety, performance). Digital twins could serve to further improve thorium reactor designs and to identify potential operational challenges and faults.

ii. Traveling Wave Reactors

In traveling wave reactors, a small quantity of *enriched* uranium or plutonium triggers a chain reaction, which showers a larger volume of *natural* and *depleted* uranium (which are abundant) with neutrons. These neutrons convert the uranium to plutonium, which is a reactor fuel.[28,30] Designs vary between static fuel systems, in which the reaction wave moves through stationary fuel arrays, and standing wave designs, in which the reaction front is maintained in place by moving the fuel.

Given the early status of design and operation, an enormous number of potential AI applications could serve to test and improve traveling wave reactors. First, AI could help determine how to blend and configure the fissile trigger. It could help assess the potential for adding wastes from nuclear weapons or medical isotopes. As with thorium reactors, it could help design better, cheaper, safer reactors. And it could help anticipate novel challenges and risks from extended operation of traveling wave reactors, including potential environmental and commercial challenges.

iii. Sodium-cooled fast reactor

Sodium-cooled fast reactors (SFRs) are advanced nuclear reactors that use liquid sodium as a coolant, allowing for higher operating temperatures and lower pressures compared to water-cooled reactors. SFR technology has been demonstrated in several countries, but deployment remains limited, with only a handful of SFRs reactors currently operating. Their “fast” neutrons have more energy, so they can split more kinds of atoms as fuel.[31]

Terrapower, a US company developing an SFR design, is using AI to optimize the placement and enrichment level of fuel elements.[32] AI may also be used to find weak spots in the design before construction by running multiple operating scenarios in a quick fashion.

iv. Graphite Gas-Cooled Reactors

Nuclear engineers from the University of Tennessee, Oak Ridge National Laboratory and UltraSafe Nuclear Corporation have optimized the design for a graphite-moderated, gas-cooled reactor with a core manufactured via 3-D printing. Use of 3-D printing has liberated designers from uniformly shaped components. The technique, also called additive manufacturing, allows fabrication of cooling channels of varying radius—even variable radius over its length—and the channel’s path through the graphite does not have to be straight. Their design is for a 3-megawatt core, measuring 1 meter high and 80 centimeters in diameter. Its size gave rise to the informal name, “the trash can reactor.” At the moment, this design is conceptual under DOE’s Transformational Challenge Reactor program.

In developing their “trash can reactor,” researchers at the University of Tennessee used AI to help optimize their design. “A human can do it, but it’s difficult for the human to do it precisely,” said Vladimir Sobes, assistant professor of nuclear engineering at the University of Tennessee, Knoxville and lead author of a paper describing the process. “The human gets the intuition very well in terms of directionality, but not in terms of precise numbers.” In their case, the AI program applied computational fluid dynamics techniques to 750 designs to find the best configuration.[33]

v. Networking fleets of new reactors

Part of making nuclear power cost-competitive is getting economies of scale in reactor operations—not just construction—and making best use of human resources across a fleet. Today, nuclear power plants differ enough from each other that each needs its own engineering and maintenance.

Maintenance is conducted mostly based on the condition of components, as observed by local staff. But a family of new reactors could pool their data, and some engineering and maintenance functions could be centralized. Utilities that operate fleets of reactors have already centralized their engineering and maintenance to improve efficiency, but AI may allow additional centralization.

X-energy, for example, is developing a gas-cooled, graphite-moderated small reactor, which it intends to deploy in four-packs. However, all the four-packs will be wired together, and AI at a regional plant support center will analyze their pooled data.[34] This arrangement should permit predictive maintenance based on data gathered from components, including temperature, vibration and similar parameters, which will indicate whether to increase or decrease the maintenance interval. This approach contrasts with the legacy approach of refurbishing solely based on time intervals or equipment cycles.

The system can also optimize the supply chain, determining what parts need to be kept in inventory and how fast they will be consumed. Humans will still be in the loop, according to the company, and it does not plan to use AI in the moment-to-moment operation of the plants.[a]

FUSION

Can AI help make fusion energy practical? The date predicted for that milestone is has always been floating a few years in the future, and the pathway is still unclear. There is, however, some early work in applying AI to this challenge.

Researchers at the Princeton Plasma Physics Laboratory have used AI to attack a central problem of magnetic fusion, which is to keep the plasma field together, a prerequisite for maintaining the terrific temperatures and pressures needed to fuse atoms. AI has analyzed previous experimental work in making plasma fields in a tokamak and can now predict one type of instability that causes plasma fields to break down, called tearing mode instabilities. AI can give notice of 300 milliseconds, which is short (about three times the duration of a blink of an eye), but potentially long enough for a computer-controlled system to make adjustments to prevent the tearing. Researchers have used AI to change the shape of the plasma and the strength of the beams that add power to it. Thus far, they have applied AI to one type of instability at one tokamak, which uses a magnetic field to keep the plasma together, so the work is still preliminary.[36]

AI has also been used to help with another approach to fusion—inertial confinement. Engineers at Lawrence Livermore National Laboratory used AI to study hundreds of thousands of computer simulations to improve the way the fuel is confined.[37] Lawrence Livermore sustained a fusion reaction in December 2022 that produced more energy than was used to create the event.

C. Nuclear waste

One of the most vexing and persistent concerns about nuclear energy is the back end of the fuel cycle: waste management. Although nuclear waste is safely managed today through a variety of approaches, public concerns persist regarding safe handling and disposal of waste fuel and nuclear residues. Advances in AI can potentially improve the end of the nuclear fuel cycle

[a] NRC Chairman, Christopher T. Hanson, reiterated in testimony before a House Energy & Commerce subcommittee on July 23 that his agency's position is that humans must remain in the loop.[35]

i. Dry Cask Storage

Most operating plants around the world have on-site interim storage of spent fuel rods in specially designed and operated pools. When pools become full, the rods are most commonly placed into dry casks, comprising a metal sheath and concrete. The dry casks are designed to hold fuel rods indefinitely, with most common dry-cask performance estimates of ~100 years of storage, with some estimates of 1800 years.[38] Dry casks are commonly stored above ground and can be shipped safely.

AI has the potential to improve the design and performance of dry cask storage. In part, this is due to the long history and sustained study and monitoring of the casks, which produced data that might serve as AI training data sets. For example, AI has helped better identify damage and functional anomalies,[39] and is a central component of systems for automatic damage detection.[40] AI tools could also optimize storage system components in terms of pressure, temperature, composition and loadings; improve material design for storage cladding and casing alloys; and predict the performance of existing systems. [41,42]

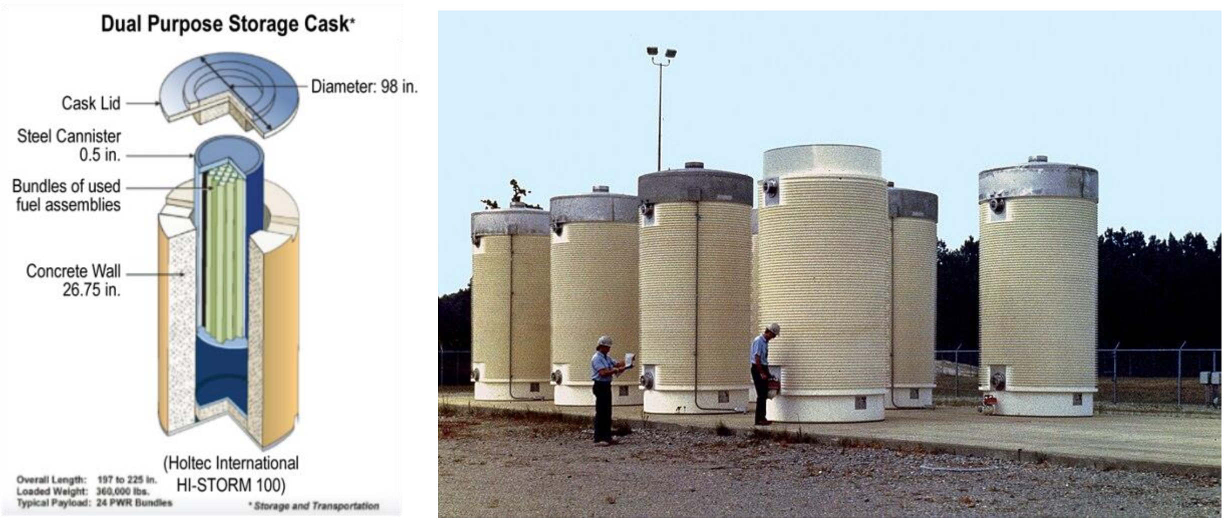

Figure 10-5. Dry casks for spent nuclear fuel. Left: Schematic diagram of a cask for storage and shipping and description of the materials used in its construction. Right: Dry-cask storage containers in the field. Source: US NRC[43]

ii. "Conventional" Geological Repositories

The scientific consensus is that the long-term solution for containing and disposing of spent nuclear fuel is dedicated geological repositories. According to the Nuclear Energy Association (NEA), "Deep geological disposal is widely agreed to be the best solution for final disposal of the most radioactive waste produced".[44] Today, some long-lived waste from weapons production and maintenance is buried at the Waste Isolation Pilot Plant (WIPP) facility in New Mexico,[45,46] which has operated since 1999 and has received over 14,000 shipments of trans-uranic waste. The Onkalo facility in Finland,[47] the first facility dedicated to civilian high-level nuclear waste storage, could open as early as 2026 with the goal of 100,000-year containment.

These facilities are highly complicated in design, site characterization, operation, fault detection, monitoring (sensors and controls) and performance assurance. AI applications across these disciplines could deliver improvements in materials, design and operational performance.[48] Potential improvements could include understanding mineralogical response,[49] better corrosion resistance and management (see below), improved fault detection, heat management, optimized loading of storage cannisters[50] and rapid assessment of environmental hazards. AI could also help find the most promising locations for geological repositories.[51] To better understand these potential opportunities, the NEA convened a working group in 2023 to explore applications to radioactive waste storage,[52] with its report and recommendations anticipated in 2025.

iii. Alternative Waste Management Strategies

Finally, AI might help operators, managers and regulators consider novel approaches to nuclear waste storage. One promising approach, deep borehole disposal (DBD), would place waste containers into specially designed boreholes that are 5 km deep or more. AI has many potential applications in this approach, including identifying promising borehole sites, optimizing container design, or far-field detecting of disposal breaches.

Another potential approach involves separating certain radioactive isotopes in nuclear waste and transmuting them into new elements that do not need to be isolated for so long (e.g., by bombarding long-lived isotopes with neutrons to convert them to materials with shorter half-lives).[53] Possible benefits of processing and partitioning wastes followed by transmutation include recovering some elements for re-use in fuels and reducing total waste volumes.[54,55] Although promising, transmutation is an immature technology that needs advanced technology.[56,57] In considering functional transmutation systems, some workers have already turned to AI and ML applications to provide insight.[58] Potential applications include optimizing energy and performance for isotope separation and designing neutron beams and specialty materials for transmutation system components.

D. Nuclear regulatory process

Regulators enforce the obligation of plant operators to ensure that power reactors remain safe. As technology advances, the integration of AI into regulatory activities represents a promising avenue for enhancing oversight and efficiency of enforcement. AI algorithms could be deployed to analyze maintenance and performance data from nuclear power reactors, enabling more predictive decision-making. For instance, AI-powered analytics could identify emerging safety trends or anomalies in reactor performance, allowing regulators to prompt the licensees to take preemptive measures to address issues before they escalate. Additionally, AI-driven automation could streamline regulatory processes, such as inspections and licensing reviews, by focusing regulators on the most important areas, optimizing resource allocation and accelerating assessment of compliance with safety standards.

However, integrating AI into regulatory activities also presents challenges. Ensuring reliability and transparency of AI algorithms used in regulatory decision-making will be paramount to maintaining public trust and confidence in the regulatory process. Rigorous testing, validation and monitoring of

AI systems will be necessary to mitigate the risk of biases, errors or unintended consequences. Furthermore, regulatory bodies will need to develop robust frameworks and standards for ethical and responsible use of AI, particularly concerning data privacy, security and accountability. Collaborative efforts with industry stakeholders, research institutions and AI experts will be essential for navigating these challenges and harnessing the full potential of AI to enhance nuclear safety and regulatory oversight.

A few regulatory bodies have already started exploring and testing AI systems through hosting workshops, engaging industry stakeholders, seeking public input and using "sandboxing" techniques.

AI sandboxing is an activity in a controlled environment where AI algorithms and new technologies are tested, validated and refined virtually before deploying them in the real world. The primary objective of AI sandboxing is to mitigate risks associated with adopting AI, such as algorithmic bias, safety lapses and regulatory non-compliance, while also fostering innovation and collaboration within the AI ecosystem.[59]

AI sandboxing is not limited to nuclear power. In October 2023, President Biden issued an executive order on the use of AI that called for "robust, reliable, repeatable and standardized evaluations of AI systems." The order requires the Secretary of Energy to establish a plan for developing AI testbeds and to develop tools to evaluate AI's "capabilities to generate outputs that may represent nuclear, nonproliferation, biological, chemical, critical infrastructure and energy-security threats."[60]

Here are initiatives taken in several countries:

i. United States

The NRC's work to understand AI developments in the US nuclear industry dates to at least 2021, when the NRC issued a Federal Register notice to solicit comments from the industry about AI and organized a series of workshops on data science and AI regulatory applications. This created a forum for NRC, the nuclear industry and various stakeholders to discuss the state of knowledge on AI applications in the nuclear industry.[61]

In 2022, the NRC issued NUREG/CR-7274, "Exploring Advanced Computational Tools and Techniques and Artificial Intelligence and Machine Learning in Operating Nuclear Power Plants," which documented the state of practice of AI applications in the nuclear industry. In the same year, the NRC published the "Artificial Intelligence Strategic Plan" for fiscal years 2023–2027. The AI Strategic Plan established "the vision and goals for the NRC to cultivate an AI-proficient workforce, keep up pace with AI technological innovations, and ensure the safe and secure use of AI in NRC-regulated activities."[62] The AI Strategic Plan includes five goals[62]:

1. Ensure NRC readiness for regulatory decision-making
2. Establish an organizational framework to review AI applications
3. Strengthen and expand AI partnerships
4. Cultivate an AI-proficient workforce
5. Pursue use cases to build an AI foundation across the NRC[62]

There are some roles for AI that do not appear to raise safety implications. The NRC maintains the Agency-wide Documents Access and Management System, known as ADAMS, that is notoriously hard to use. In an age when other documents can be located by commercial search engines, ADAMS remains mostly opaque because search engines like Google work by examining links between documents, and ADAMS does not link documents.

But two companies have downloaded the entire ADAMS corpus and are using AI tools to make it searchable. Microsoft has done this on behalf of TerraPower, which is building a reactor plus storage project in Wyoming. And a startup called Atomic Canyon is seeking to make ADAMS searchable so that companies preparing license applications can find useful precedents. Similar to other technical fields like medicine and law, regulating nuclear energy is a specialized field with specialized vocabulary. This adds a layer of challenge in making ADAMS searchable since general purpose large language models (LLMs) may struggle with correctly interpreting and processing technical language, such as that found in the 50 million documents in ADAMS. (See Chapter 11 for a discussion of LLMs.)

A more easily searchable ADAMS would help applicants for licenses find relevant precedents—and solutions—for the technical issues they face.

A 2024 workshop report from Argonne National Laboratory identified three areas where AI could assist nuclear power to make a larger contribution to addressing energy and environmental challenges: (1) accelerating the licensing and regulatory process, (2) accelerating deployment and (3) facilitating maintenance scheduling and autonomous operation. (AI control of robotic maintenance or cleanup equipment seems more likely, though, than AI replacing control room operators.) Regarding the analysis and licensing of new reactors, studies have looked at the potential for digital engineering and digital twinning technologies (a nuclear digital twin is the virtual representation of a nuclear power system) to be applied to reactor design and construction, which could help with the economics of future reactors.

ii. United Kingdom

The United Kingdom's Office for Nuclear Regulation (ONR) is a leader in exploring the potential benefits and challenges of AI in nuclear power. ONR and the UK Environment Agency have consulted with a wide range of stakeholders on AI and are piloting an AI sandboxing initiative aimed at fostering innovation and exploring the potential applications of AI in nuclear regulatory processes “in the interest of safety, security and environmental protection.”[63](See ONR, 2023 at p. 5[64]) In November 2022, the UK Department for Business, Energy and Industrial Strategy awarded ONR and the Environment Agency a grant of £170,950 through the Regulators’ Pioneer Fund to deliver the sandboxing pilot project (see ONR, 2023 at p. 5[64]).

The ONR has been exploring regulatory sandboxing for AI, consulting with the UK Environment Agency, the UK Civil Aviation Authority and others on topics including the use of AI-enabled robots in constrained spaces (see ONR, 2023 at p. 9 and 11[64]). Engagement sessions conducted during the project have sparked increasing stakeholder interest in the sandboxing approach and AI integration. Key findings include the necessity to clearly articulate AI benefits compared to traditional technologies, the importance of understanding and managing AI-related risks and of phased deployment for confidence-building, and the need for a principles-based regulatory approach. Stakeholders also highlighted challenges in substantiating AI reliability. They stressed the importance of thorough hazard analysis for different AI deployment modes and identified three key areas for skill and guidance development: access to AI expertise, operational experience and fostering a safety-centric culture. Moreover, stakeholders underscored the complexity of human/system interaction in AI deployment and advocated for disseminating guidance and good practices, focusing initially on principles and case studies to aid stakeholders in navigating AI deployment and regulation (see ONR, 2023 at p. 6–7[64]).

iii. Canada

The Canadian Nuclear Safety Commission (CNSC) has taken several steps with regards to AI. From 2019 to 2020 the CNSC established a working group to assess the implications of disruptive, innovative and emerging Technologies (DIET) for its regulatory framework.[65,66] In 2023, under the DIET initiative, CNSC along with Candu Energy, Inc. released a report titled "A Study for the Canadian Nuclear Safety Commission on Artificial Intelligence Applications and Implications for the Nuclear Industry"(See CNSC, 2023 at p. 5[67]). The report reviews current applications of AI in the nuclear industry and regulatory efforts by the International Atomic Energy Agency (IAEA), US NRC and UK ONR. The report assesses the regulatory framework of the CNSC, providing strategic recommendations on how it can better support licensees in safely and effectively integrating AI technologies "(see CNSC, 2023 at p. 15[67]) and analyzes AI applications in safety-centric industries, including nuclear power, oil and gas, medicine, and aviation. The report highlights data integrity as crucial to preventing AI failures, maintaining performance and meeting safety standards in these industries (see CNSC, 2023 at p. 15[67]).

Three areas have emerged as regulatory challenges for CSNC with respect to AI: reliability, trustworthiness and security. The 2023 report provides recommendations to address all three (see CNSC, 2023 at p. 48–49[67]):

1. AI reliability in nuclear facilities. Prior to deployment, demonstrate that AI performance meets established metrics. Implement use of AI in phases, with parallel human-in-the-loop validation. Transition to fully autonomous operation once AI reliability is confirmed. Implement real-time monitoring to continuously assess algorithm and data reliability.
2. AI trustworthiness in nuclear facilities. AI engineers and technicians should collaborate with standard-setting bodies to develop uniform practices and software evaluation methodologies. Personnel should be educated continuously to stay updated with technological advancements and regulatory requirements, ensuring safe and effective AI integration in nuclear activities.
3. AI security. Develop algorithms in secure environments, conduct pre-implementation evaluations for malicious code, continuously monitor model access and usage to prevent manipulation, and enforce strict access controls to protect sensitive information.

The report by CNSC, the UK ONR and the US NRC published in September 2024 emphasizes the importance of applying safety and security systems engineering principles when integrating AI into nuclear applications. Since current regulations do not specifically address AI, regulators require nuclear licensees to identify applicable standards and potential gaps. A recommended strategy is to utilize the simplest technologies alongside AI to reduce uncertainty and enhance safety. This includes performing gap analyses to explore both AI-based and conventional risk mitigation strategies, especially in scenarios where AI failures could have severe consequences. The report advocates for robust recovery plans, risk management principles such as diversity and redundancy, and a multilayered defense approach to avoid reliance on any single aspect of the AI system (see Lee et al., 2024 at p. 6[68]).

The report stresses that human and organizational factors play a critical role in AI deployment within nuclear operations. Clear definitions of human and AI roles are essential for human-machine collaboration, as many AI systems are designed to augment rather than replace human decision-making. Concerns regarding the "black box" nature of AI necessitate monitoring AI performance and allowing for human intervention when needed (see Lee et al., 2024 at p. 9–10[68]). Ongoing training programs and evaluations of safety culture are vital for ensuring that AI integration aligns with safety priorities. Additionally, the report outlines high-level principles for managing the AI life-cycle, highlighting the importance of iterative processes in design, development and deployment, while stressing the need for continuous monitoring to address issues like data drift and model biases. Finally, the report emphasizes the need for thorough documentation and innovative testing methods for demonstrating the safety and reliability of AI (see Lee et al., 2024 at p. 15[68]).

iv. Japan

The Japanese Nuclear Regulation Authority (NRA) has been using AI since 2019 for automated transcription of meetings with industry representatives. The AI tools are used to help increase transparency of NRA operations.[69] The NRA is also expected to use AI tools to help process data collected under an agreement with the IAEA regarding inspection procedures at Japanese research reactors and other nuclear research and development (R&D) facilities (see Siserman-Gray et al, 2023 at p. 7[70]). In response to a request from a member of the NRA, the NRA’s Technology Platform Group conducted a survey on technological trends in the nuclear power sector, which was released in March 2024.[71]

The Japan Atomic Energy Agency and Nagoya University have developed AI tools to create radiation maps from data collected by drones. These tools significantly improve accuracy and reduce analysis time, helping map radiation in the Fukushima Daiichi Nuclear Power Plant evacuation zone.[72]

The Japanese government is using AI to identify social media postings it believes to be incorrect regarding the release of treated wastewater from the Fukushima nuclear power plant.[73] The Japanese government’s AI Strategy, released in 2022, highlights potential roles for AI in the power sector but does not specifically mention nuclear power.[74]

E. Barriers

Several barriers limit the use of AI for nuclear power. In an industry that relies on a public confidence in both the nuclear plants and the regulators, employing a technology susceptible to “hallucinations” could be counterproductive, even if experts were convinced that the technology was being used in safe ways. A text-based system that urges a user to divorce his wife because she does not really love him[75] or includes glue in a pizza recipe[76] could make members of the public who are already skeptical or opposed to nuclear power even more so. Additional barriers include:

- Development of AI technology in the nuclear sector is severely inhibited by lack of data in digital format from power reactors. The data that do exist are mostly for non-power reactors operated by national laboratories and other institutions.
- Lack of domain awareness and expertise within the AI community also impedes development of AI for nuclear power. With nuclear expertise strongly concentrated in a handful of highly specialized institutions, it is challenging for non-experts to gain knowledge about nuclear power, which limits scalable development of AI within this application area. Overall, interfacing between the highly specialized nature of both AI and nuclear power requires significant training and skills-development. Professional societies could ameliorate the problem by providing educational opportunities and supporting development of best practices and standards.
- Nuclear power has, by far, the most stringent regulatory oversight in the energy sector. The safety and security requirements of nuclear power are a high barrier for AI applications to overcome, deterring AI development and deployment.
- Current rules flatly forbid using AI in one place where advanced reactor developers say it could be very useful: operating micro-reactors. The industry is moving toward reactors that put out only a few megawatts, but these cannot be an economic success if they carry the full complement of control room operators that big plants do today. In fact, they might be able to run with no more than a local "monitor," someone at the plant or on call, as some diesel generators and gas turbines do. But this would require a new mindset at the NRC, which has not given any public indication that it is moving in that direction. The current rule says only a licensed operator can adjust the power level.[77]
- The nuclear sector has a conservative professional culture and late-adopter strategy when it comes to new technologies such as AI, a technology subject to rapid change and improvements

F. Risks

The use of AI for nuclear power creates a number of risks:

- AI methods used as part of nuclear planning, simulation and other off-line activities that involve close human scrutiny pose little or no additional risk over existing approaches. Additional risk arises only if the "humans-in-the-loop" give too much or misplaced weight to results derived from AI.
- The primary risk of AI in nuclear operations pertains to on-line applications. If AI-based analyses, predictions or optimizations are used in time-constrained "real-time" decision-

making workflows, their reliability must be taken into account to minimize the risk of catastrophic operational failure.

- AI methods that adapt to real-time conditions require data networks that pipe data from sensors to servers. If these networks are exposed to other networks or the internet broadly, the application of AI can introduce a new set of cybersecurity risks. Nuclear operators and regulators must clearly evaluate and mitigate these risks.
- AI methods are traditionally tested against plentiful data, which enables rigorous evaluation of their expected performance once deployed. Data scarcity within the nuclear sector raises a risk of insufficient validation of AI methods prior to deployment. Prematurely deployed AI methods may lead to insights, predictions and optimizations that are less effective than traditional approaches. In real-time applications, prematurely deployed AI carries additional operational safety and security risks.
- The potential negative consequences of catastrophic operational failure at nuclear power plants are very high. As a result, extreme caution is required by all parties, from regulators to operators, in introducing any new technology, including AI, into nuclear power operations. For example, the consequences of AI-induced hallucinations could be very large. In addition, AI-operated control systems could present a new vector for cyberattacks with new vulnerabilities to their specific design and function. Additional care is needed to harden such systems, and additional points of intervention and override may be needed to avoid dangerous or poor outcomes.
- Deploying AI within nuclear operations and maintenance may eventually eliminate certain jobs in the nuclear sector. While this is likely a net positive in terms of minimizing human health and safety risk within nuclear operations, it may be perceived as an economic and political risk.

G. Recommendations

1. *Nuclear regulators should be open to AI playing a role in reactor design, safety analyses and recommendations for operating procedures. The operative question is the quality of the work product, not the identity of the designer. All designs, analyses and procedures, whatever their origin, should be run through rigorous reviews. Additional oversight, checks and security hardening may be part of this work.*

2. *Plant owners and regulators should assure that AI will be used only in advisory and alerting roles. Nuclear plant operators should play the same role in a plant that uses AI as in a plant that does not. The operator should not become like a car driver who plays video games while driving; humans must remain in the loop, engaged and active, despite the routine work performed by AI. Nuclear plant owners should look at the experience in aviation, power and other relevant industries.*

3. *The civilian nuclear industry should scrutinize AI technologies funded by government dollars through science R&D agencies for applicability to their operations.*

4. *Nuclear regulatory bodies should be preparing for license requests from microreactor companies that include a role for AI in remote control.*

5. *Regulators should consider employing the UK ONR's initiative to test different AI technologies in a controlled environment to understand AI's potential to enhance various aspects of nuclear operation and regulation ("sandboxing"). Through sandboxing, regulators can test, refine and evaluate the algorithms within the context of nuclear safety.*

6. *Government innovation agencies should integrate AI into their research, development and demonstration (RD&D) plans. Key foci of innovation investments should include sustaining the existing fleet, advanced reactors, and non-electric applications of nuclear energy*

7. *Plant owners should engage with the scientific community to provide access to high-quality data that can drive AI development and deployment. Professional societies should support development and dissemination of best practices in gathering, annotating, hosting and sharing such data.*

8. *Professional societies should offer educational resources and training to attract the attention of the AI community to the nuclear sector. These societies should also reach out to computer science academic departments, professional computer science societies and government agencies to encourage development of AI skills within the nuclear sector.*

9. *Nuclear regulatory agencies should hire staff with AI expertise to efficiently evaluate and recommend adoption of high value-add AI applications in nuclear power.*

H. References

1 Brent Wanner & Ryota Taniguchi. *Nuclear Power;* International Energy Agency (IEA), Paris, France, https://www.iea.org/energy-system/electricity/nuclear-power (Accessed August 2024).

2 Energy Institute. *Statistical Review of World Energy;* London, UK, https://www.energyinst.org/statistical-review (Accessed August 2024).

3 Slade Johnson & Jonathan Russo. *China continues rapid growth of nuclear power capacity;* US Energy Information Administration, Washington, D.C., https://www.eia.gov/todayinenergy/detail.php?id=61927 (2024).

4 World Nuclear Association. *Country Profiles: Nuclear Power in Japan;* London, UK, https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power (Accessed August 2024).

5 Jennifer Hiller. *A Massive U.S. Nuclear Plant Is Finally Complete. It Might Be the Last of Its Kind.;* The Wall Street Journal, New York, New York, https://www.wsj.com/business/energy-oil/a-massive-u-s-nuclear-plant-is-finally-complete-it-might-be-the-last-of-its-kind-0c0f6e44 (2024).

6 World Nuclear Association. *Country Profiles: Nuclear Power in Spain;* London, UK, https://world-nuclear.org/information-library/country-profiles/countries-o-s/spain (Accessed August 2024).

7 Rumyana Vakarelska. *Flamanville-3 / Fuel Loading Begins At France's Delayed EPR Nuclear Power Plant;* NucNet, Brussels, Belgium, https://www.nucnet.org/news/fuel-loading-begins-at-flamanville-3-epr-nuclear-plant-in-normandy-5-4-2024 (2024).

8 Energy Education. *Boiling water reactor;* University of Calgary, Calgary, Alberta, Canada, https://energyeducation.ca/encyclopedia/Boiling_water_reactor (Accessed August 2024).

9 Derjew Ayele Ejigu, Yanjie Tuo & Xiaojing Liu. Application of artificial intelligence technologies and big data computing for nuclear power plants control: a review. *Frontiers in Nuclear Engineering* 3 (2024). 10.3389/fnuen.2024.1355630.

10 Idaho National Laboratory. *Artificial Intelligence and Machine Learning;* Idaho Falls, Idaho, https://inl.gov/artificial-intelligence/ (Accessed August 2024).

11 Rob Austin & Thiago Seuaciuc-Osorio. *Quick Insight Brief: Leveraging Artificial Intelligence for the Nuclear Energy Sector;* Electric Power Research Institute (EPRI), Palo Alto, California, https://www.epri.com/research/products/000000003002021067 (2021).

12 Blue Wave AI Labs. *Home Page;* West Lafayette, Indiana, https://www.bluewaveailabs.com/ (Accessed August 2024).

13 Jonathan Nistor Chief Operating Officer of Blue Wave Labs & Tom Gruenwald Co-Founder and Senior Vice President of Blue Wave Labs. (Zoom interview, April 11, 2024).

14 David McIntire of the US Nuclear Regulatory Commission (NRC). (ed Matthew L. Wald) (July 31, 2024).

15 NuclearN. *Home Page: NuclearN isArtificial Intelligence for the Nuclear Industry;* Phoenix, Arizona, https://nuclearn.ai/ (Accessed August 2024).

16 D. K. Wehe *et al.* 10. Intelligent robotics and remote systems for the nuclear industry. *Nuclear Engineering and Design* 113, 259-267 (1989). https://doi.org/10.1016/0029-5493(89)90077-0.

17 Boston Dynamics. *Home Page: Spot® - The Agile Mobile Robot;* Waltham, Massachusetts, https://bostondynamics.com/products/spot/ (Accessed August 2024).

18 Barry Lennox at University of Manchester. *Robotics and Artificial Intelligence for Nuclear (RAIN);* UK Research and Innovation, Swindon, UK, https://gtr.ukri.org/projects?ref=EP%2FR026084%2F1 (Accessed August 2024).

19 RIMA Network Alliance. *RIMA: Robotics for Inspection and Maintenance;* https://rimanetwork.eu/ (Accessed August 2024).

20 Organisation for Economic Co-operation and Development (OCED) Nuclear Energy Agency (NEA). *Expert Group on the Application of Robotics and Remote Systems in the Nuclear Back-end (EGRRS);* Boulogne-Billancourt, France, https://www.oecd-nea.org/jcms/pl_25235/expert-group-on-the-application-of-robotics-and-remote-systems-in-the-nuclear-back-end-egrrs (Accessed August 2024).

21 Erico Guizzo. *Fukushima Robot Operator Writes Tell-All Blog;* Institute of Electrical and Electronics Engineers (IEEE) Spectrum, New York, New York, https://spectrum.ieee.org/fukushima-robot-operator-diaries (2011).

22 Stephen D. Monk *et al.* Implementation and Evaluation of a Semi-Autonomous Hydraulic Dual Manipulator for Cutting Pipework in Radiologically Active Environments. *Robotics* 10, 62 (2021). https://doi.org/10.3390/robotics10020062.

23 Ozan Tokatli *et al.* Robot-Assisted Glovebox Teleoperation for Nuclear Industry. *Robotics* 10, 85 (2021). https://doi.org/10.3390/robotics10030085.

24 Declan Shanahan, Ziwei Wang & Allahyar Montazeri. Robotics and Artificial Intelligence in the Nuclear Industry: From Teleoperation to Cyber Physical Systems in *Artificial Intelligence for Robotics and Autonomous Systems Applications* (eds Ahmad Taher Azar & Anis Koubaa) 123-166 (Springer International Publishing, Cham, 2023, https://doi.org/10.1007/978-3-031-28715-2_5).

25 Amani Cheniour, Amir Koushyar Ziabari & Yann Le Pape. A mesoscale 3D model of irradiated concrete informed via a 2.5 U-Net semantic segmentation. *Construction and Building Materials* 412, 134392 (2024). https://doi.org/10.1016/j.conbuildmat.2023.134392.

26 Richard Vilim & Lander Ibarra. Artificial Intelligence/Machine Learning Technologies for Advanced Reactors (Workshop Summary Report). Medium: ED; Size: 32 p. (United States, 2022; https://doi.org/10.2172/1861306).

27 Isabelle Dumé. *Can thorium compete with uranium as a nuclear fuel?;* Polytechnique Insights (A Review by Insititut Polytechnique de Paris), Palaiseau, France, https://www.polytechnique-insights.com/en/braincamps/energy/the-latest-technological-advances-in-nuclear-energy/can-thorium-compete-with-uranium-as-a-nuclear-fuel/ (2022).

28 Wikipedia. *Thorium-based nuclear power;* San Francisco, California, https://en.wikipedia.org/wiki/Thorium-based_nuclear_power#:~:text=Thorium%2Dbased%20nuclear%20power%20generation,A%20sample%20of%20thorium (Accessed August 2024).

29 International Atomic Energy Agency (IEAE). *Thorium's Long-Term Potential in Nuclear Energy: New IAEA Analysis;* Vienna, Austria, https://www.iaea.org/newscenter/news/thoriums-long-term-potential-in-nuclear-energy-new-iaea-analysis (2023).

30 T. Ellis *et al. Traveling-wave reactors: A truly sustainable and full-scale resource for global energy needs*. (American Nuclear Society - ANS, United States, 2010, http://inis.iaea.org/search/search.aspx?orig_q=RN:42097751).

31 The Generational IV (GenIV) International Forum (GIF). *Sodium-Cooled Fast Reactor (SFR);* https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr#:~:text=The%20SFR%20uses%20liquid%20sodium,requires%20a%20sealed%20coolant%20system (Accessed August 2024).

32 Eric Williams Senior Vice President of Engineering at Terrapower. (ed Matthew L. Wald) (Telephone Interview, May 1 2024).

33 University of Tennessee Assistant Professor Vladimir Sobes. (ed Matthew L. Wald) (Telephone Communication, May 9 2024).

34 X-energy. *X-energy to Open First Plant Support Center for Xe-100 Advanced Small Modular Reactor Fleet;* Rockville, Maryland, https://x-energy.com/media/news-releases/x-energy-to-open-first-plant-support-center-for-xe-100-advanced-small-modular-reactor-fleet (2023).

35 US House on Committee on Energy and Commerce. *Energy Hearing: The Fiscal Year 2025 Nuclear Regulatory Commission Budget;* YouTube, San Bruno, California, https://www.youtube.com/watch?v=cxgja_3ndDohttps://www.youtube.com/watch?v=cxgja_3ndDo (2024).

36 Jaemin Seo *et al.* Avoiding fusion plasma tearing instability with deep reinforcement learning. *Nature* 626, 746-751 (2024). https://doi.org/10.1038/s41586-024-07024-9.

37 Jeremy Thomas. *High-performance computing, AI and cognitive simulation helped LLNL conquer fusion ignition;* Lawrence Livermore National Laboratory (LLNL), Livermore, California, https://www.llnl.gov/article/49911/high-performance-computing-ai-cognitive-simulation-helped-llnl-conquer-fusion-ignition (2023).

38 US Nuclear Regulatory Commission. *Questions and Answers – Spent Fuel Pool Safety;* Rockville, Maryland, https://www.nrc.gov/waste/spent-fuel-storage/faqs.html#gen7 (Accessed August 2024).

39 Bozhou Zhuang *et al.* Machine learning-aided damage identification of mock-up spent nuclear fuel assemblies in a sealed dry storage canister. *Engineering Applications of Artificial Intelligence* 128, 107484 (2024). https://doi.org/10.1016/j.engappai.2023.107484.

40 Theodore Papamarkou *et al.* Automated detection of corrosion in used nuclear fuel dry storage canisters using residual neural networks. *Nuclear Engineering and Technology* 53, 657-665 (2021). https://doi.org/10.1016/j.net.2020.07.020.

41 Hee Sang Yoo, Seung Hun Yoo & Eung Soo Kim. Heat transfer enhancement in dry cask storage for nuclear spent fuel using additive high density inert gas. *Annals of Nuclear Energy* 132, 108-118 (2019). https://doi.org/10.1016/j.anucene.2019.04.018.

42 Kristina Yancey Spencer, Pavel V. Tsvetkov & Joshua J. Jarrell. Optimization of dry cask loadings for used nuclear fuel management strategies. *Progress in Nuclear Energy* 108, 11-25 (2018). https://doi.org/10.1016/j.pnucene.2018.04.029.

43 U.S. Nuclear Regulatory Commission Division of Spent Fuel Storage and Transportation. *Dry Cask Storage of Nuclear Spent Fuel;* Rockville, Maryland, https://csgmidwest.org/wp-content/uploads/2022/08/Easton.pdf (2022).

44 World Nuclear Association. *Nuclear Fuel Cycle: Storage and Disposal of Radioactive Waste;* London, UK, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste (Accessed August 2024).

45 Waste Isolation Pilot Plant (WIPP). *Home Page;* Carlsbad, New Mexico, https://www.wipp.energy.gov/ (Accessed August 2024).

46 Waste Isolation Pilot Plant (WIPP). *WIPP Site;* Carlsbad, New Mexico, https://wipp.energy.gov/wipp-site.asp (Accessed August 2024).

47 World Nuclear Association. *Country Profiles: Nuclear Power in Finland;* London, UK, https://world-nuclear.org/information-library/country-profiles/countries-a-f/finland (Accessed August 2024).

48 Guang Hu & Wilfried Pfingsten. Data-driven machine learning for disposal of high-level nuclear waste: A review. *Annals of Nuclear Energy* 180, 109452 (2023). https://doi.org/10.1016/j.anucene.2022.109452.

49 Chunhui Li, Elijah O. Adeniyi & Piotr Zarzycki. Machine learning surrogates for surface complexation model of uranium sorption to oxides. *Scientific Reports* 14, 6603 (2024). https://doi.org/10.1038/s41598-024-57026-w.

50 Virginie Solans *et al.* Optimisation of used nuclear fuel canister loading using a neural network and genetic algorithm. *Neural Computing and Applications* 33, 16627-16639 (2021). https://doi.org/10.1007/s00521-021-06258-2.

51 Federal Office for the Safety of Nuclear Waste Management. *Research: Artificial intelligence in the search for a final repository?;* Government of Germany, Berlin, Germany, https://www.base.bund.de/SharedDocs/Kurzmeldungen/BASE/EN/2022/artificial-intelligence.html (2022).

52 Organisation for Economic Co-operation and Development (OCED) Nuclear Energy Agency (NEA). *The role of artificial intelligence in the future of radioactive waste management;* Boulogne-Billancourt, France, https://www.oecd-nea.org/jcms/pl_78672/the-role-of-artificial-intelligence-in-the-future-of-radioactive-waste-management (2023).

53 Organisation for Economic Co-operation and Development (OCED) Nuclear Energy Agency (NEA). *Transmutation of Radioactive Waste;* Boulogne-Billancourt, France, https://www.oecd-nea.org/trw/ (Accessed August 2024).

54 International Atomic Energy Agency (IEAE). *Implications of Partitioning and Transmutation in Radioactive Waste Management (Technical Reports Series No. 435);* Vienna, Austria, https://www.iaea.org/publications/7112/implications-of-partitioning-and-transmutation-in-radioactive-waste-management (

55 Palash Kumar Bhowmik, Md. Shafiqul Islam & Piyush Sabharwall. *Partitioning and Transmutation of Used Nuclear Fuel in Support of Geological Waste Disposal;* Idaho National Laboratory (Prepared for the U.S. Department of Energy), https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_66409.pdf (2023).

56 X. Y. Sun *et al.* Transmutation of long-lived fission products in an advanced nuclear energy system. *Scientific Reports* 12, 2240 (2022). https://doi.org/10.1038/s41598-022-06344-y.

57 Cosima Paul. *Transmutation of High-Level Nuclear Waste;* (Submitted as coursework for PH241, Stanford University), Stanford, California, http://large.stanford.edu/courses/2024/ph241/paul2/ (2024).

58 Jin Whan Bae *et al.* Deep learning approach to nuclear fuel transmutation in a fuel cycle simulator. *Annals of Nuclear Energy* 139, 107230 (2020). https://doi.org/10.1016/j.anucene.2019.107230.

59 Jon Truby *et al.* A Sandbox Approach to Regulating High-Risk Artificial Intelligence Applications. *European Journal of Risk Regulation* 13, 270-294 (2022). https://doi.org/10.1017/err.2021.52.

60 The White House. *FACT SHEET: President Biden Issues Executive Order on Safe, Secure, and Trustworthy Artificial Intelligence;* Washington, D.C., https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/30/fact-sheet-president-biden-issues-executive-order-on-safe-secure-and-trustworthy-artificial-intelligence/ (2023).

61 US Nuclear Regulatory Commission (NRC). *Artificial Intelligence Strategic Plan: Fiscal Years 2023-2027;* Rockville, Maryland, https://www.nrc.gov/docs/ML2313/ML23132A305.pdf (2023).

62 US Nuclear Regulatory Commissions (NRC). *Artificial Intelligence;* Rockville, Maryland, https://www.nrc.gov/about-nrc/plans-performance/artificial-intelligence.html (Accessed April 2024).

63 Office for Nuclear Regulation (ONR). *Artificial Intelligence;* Bootle, UK, https://www.onr.org.uk/our-expertise/innovation/artificial-intelligence/ (Accessed August 2024).

64 Office for Nuclear Regulation (ONR). *Regulators' Pioneer Fund (Department for Science, Innovation and Technology): Pilot of a regulatory sandbox on artificial intelligence in the nuclear sector;* Bootle, UK, Report available at https://onr.org.uk/news/all-news/2023/11/outcomes-of-nuclear-ai-regulatory-sandbox-pilot-published/ (2023).

65 Canadian Nuclear Society (CNS). *The Canadian Nuclear Society's Disruptive, Innovative and Emerging Technology (DIET) Division;* Toronto, Ontario, https://www.cns-snc.ca/about-cns/divisions/the-canadian-nuclear-societys-disruptive-innovative-and-emerging-technology-diet-division/ (Accessed August 2024).

66 Seamus O'Rega. *CNSC Departmental Results Report 2019–20 (at p. 10);* Canadian Nuclear Safety Commission (CNSC), Ottawa, Ontario, https://api.cnsc-ccsn.gc.ca/dms/digital-medias/CNSC_s_2019-20_Departmental_Results_Report.pdf/object (2020).

67 Canadian Nuclear Safety Commission (CNSC). *R760.1 - A Study for the Canadian Nuclear Safety Commission on Artificial Intelligence Applications and Implications for the Nuclear Industry;* Ottawa, Ontario, https://www.cnsc-ccsn.gc.ca/eng/resources/research/research-and-support-program/research-report-abstracts/research-report-summaries-2022-2023/#R760.1 (2023).

68 Kevin Lee *et al. Considerations for Developing Artificial Intelligence Systems in Nuclear Applications;* Canadian Nuclear Safety Commission (CNSC), United Kingdom Office for Nuclear Regulation (UK ONR), United States Nuclear Regulatory Commission (US NRC), https://www.nrc.gov/docs/ML2424/ML24241A252.pdf (2024).

69 Riki Iwama. *Japan's nuclear authority using AI to help make closed meetings more transparent;* The Mainichi, Osaka, Japan, https://mainichi.jp/english/articles/20190409/p2a/00m/0na/019000c (2019).

70 Cristina Siserman-Gray *et al. Regulatory Challenges Related to the Use of Artificial Intelligence for IAEA Safeguards Verification (PNNL-SA-184813);* Pacific Northwest National Laboratory (PNNL), Richland, Washington, https://resources.inmm.org/sites/default/files/2023-07/finalpaper_379_0512065638.pdf (2023).

71 Japan Nuclear Regulation Authority Technology Platform Group. *Survey Report on Technological Trends of Artificial Intelligence and Advanced Manufacturing Technology in the Nuclear Energy Sector;* Tokyo, Japan, https://www.da.nra.go.jp/view/NRA100000236?contents=NRA100000236-002-023#pdf=NRA100000236-002-023 (2024).

72 Japan Atomic Energy Agency (JAEA). *Press Releases: Creating radiation maps smarter with AI;* Tokai, Japan, https://www.jaea.go.jp/english/news/press/2021/012902/ (2021).

73 Rieko Miki. *Japan deploys AI to detect false info on Fukushima water release;* Nikkei Asia, Tokyo, Japan, https://asia.nikkei.com/Business/Technology/Japan-deploys-AI-to-detect-false-info-on-Fukushima-water-release (2023).

74 Cabinet Office (CAO) agency of the Cabinet Office of Japan. *AI Strategy 2022 (tentative translation);* Tokyo, Japan, https://www8.cao.go.jp/cstp/ai/aistratagy2022en.pdf (2022).

75 Kevin Roose. *A Conversation With Bing's Chatbot Left Me Deeply Unsettled;* The New York Times, New York, New York, https://www.nytimes.com/2023/02/16/technology/bing-chatbot-microsoft-chatgpt.html (2023).

76 Nico Grant. *Google's A.I. Search Errors Cause a Furor Online;* The New York Times, New York, New York, https://www.nytimes.com/2024/05/24/technology/google-ai-overview-search.html (2024).

77 US Nuclear Regulatory Commission (NRC). *50.54 Conditions of licenses;* Rockville, Maryland, https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0054.html (Accessed August 2024).