Nuclear Technology Review ■ 2024

Report by the Director General

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

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Contents

Summary

- In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* each year. Attached is this year's report, which highlights notable developments in 2023.

- The Nuclear Technology Review 2024 covers the following select areas: nuclear power, nuclear fuel cycle, decommissioning, environmental remediation and radioactive waste management, fusion research and technology development for future energy production, research reactors, particle accelerators and nuclear instrumentation, atomic and nuclear data, artificial intelligence in nuclear power and the nuclear fuel cycle, human health, food and agriculture, radioisotope and radiation technology, isotope hydrology and marine environment.

- The draft version was submitted to the March 2024 session of the Board of Governors in document GOV/2024/2. This final version was prepared in the light of the discussion held during the Board of Governors and also of the comments received by Member States.

Foreword by the Director General

Whether used for producing reliable and low carbon energy or for tackling food, health, water and environmental issues, nuclear technologies play an important role in addressing many of our most pressing challenges.

In 2023, we saw continued strong interest in nuclear power, to meet both climate objectives and the challenge of secure and affordable energy, with several Member States revising their nuclear energy policies. At the 28th Conference of the Parties (COP28) of the United Nations Framework Convention on Climate Change (UNFCCC), held in Dubai, United Arab Emirates, the Agency held a series of events at the Atoms4Climate Pavilion featuring how nuclear energy could contribute significantly to decarbonizing hard to abate sectors and hydrogen production, fostering fast decarbonization. The IAEA Statement on Nuclear Power, endorsed by dozens of Member States was released on 1 December 2023, emphasizing how net zero needs nuclear power. This had been confirmed a few months earlier by the International Energy Agency's updated Net Zero by 2050 road map, which sees nuclear capacity more than doubling by 2050, in line with the IAEA's own high case projections released in September 2023. Furthermore, during COP28, a Declaration by more than 20 countries called for tripling nuclear capacity by 2050 and invited regional development banks and international financial institutions to include nuclear in their lending policies, while underscoring the need for secure supply chains to ramp up deployment of the technology. Together with our partners, and as a result of previous years' efforts and determination, for the first time since the annual climate summits commenced in 1995, COP28 closed with major achievement. In its first Global

FIG. FW.1. IAEA Director General Rafael Mariano Grossi speaking at COP28 in Dubai, United Arab Emirates. (Photo: IAEA)

Stocktake approved by the 198 signatory countries to the UNFCCC, “nuclear” was mentioned explicitly as one of the low emission technologies needed to achieve deep and rapid reductions in greenhouse emissions.

At the same time, a growing number of countries are using nuclear technologies for non-power applications, including to strengthen food security, tackle the effects of climate change, protect the environment from pollution and improve care for cancer and other life-threatening diseases. As the present report highlights, the Agency continues to innovate in these and other key areas through the work of its nuclear applications laboratories in Austria and Monaco, coordinated research projects and partnerships with leading research institutions worldwide. In many areas of the Agency’s research and development activities, artificial intelligence is increasingly being used to help drive innovation, a trend that will continue to grow.

Scientific research and data are the bedrock of informed decision making, and the Agency constantly seeks opportunities where its research and development activities can help countries make the most of nuclear sciences and technologies to protect and improve the health and well-being of their people. Following upon the Agency’s Zoonotic Disease Integrated Action (ZODIAC), Nuclear Technology for Controlling Plastic Pollution (NUTEC Plastics) and Rays of Hope initiatives, with food insecurity on the rise globally in 2023, the Agency and the Food and Agriculture Organization of the United Nations launched a joint initiative, Atoms4Food, to support countries in increasing food and nutrition security using nuclear techniques, including through climate-smart agriculture and improved water resources management practices developed in our laboratories.

For decades, nuclear science and technology have been important tools for helping countries meet their development needs. They can certainly do more, and in more areas. By highlighting some of the key developments in nuclear technology in 2023, the *Nuclear Technology Review 2024* will help Member States make informed decisions when addressing both current and new challenges.

Executive Summary

For the third successive year, the Agency has revised up its annual projections of the potential growth of nuclear power during the coming decades, confirming renewed interest in nuclear power in the context of energy security and climate change crises, as well as increased electrification demand and the need to find alternatives to fossil fuels to supply heat and hydrogen to decarbonize the industrial and transport sectors. The Agency has increased its low case projection to 458 gigawatts (GW) in 2050, representing a significant increase of 55 GW compared to the 2022 low case projection. The high case projection has increased to 890 GW in 2050, up from 873 GW in the previous year's high case projection and representing a 175 GW increase compared to the 2020 projection.

As of December 2023, the global operational nuclear power capacity was 371.5 GW(e), provided by 413 reactors across 31 Member States. Furthermore, 21.3 GW(e) (25 reactors) of licensed operational capacity remained in suspended operations throughout the year. During 2023, 5 GW(e) of new nuclear power capacity from 5 reactors was connected to the grid, and an additional 1.6 GW(e) was restored by two reactors that had previously been in suspended operations and reconnected to the grid. Reports from Member States indicate that the global nuclear power fleet generated approximately 2515.2 terawatt-hours (TWh) of low-emission, dispatchable electricity.[1] At the end of 2023, a total capacity of 61.1GW(e) (59 reactors) was under construction in 17 countries. About 67% of the world's operational reactor capacity has been in use for over 30 years. During the same period, 6 GW(e) of nuclear capacity (5 reactors) were permanently taken offline.

There are currently some 50 countries that have an interest in adding nuclear power to their energy mix. Among them, 27 countries are in different phases of initiating and implementing their national nuclear power programme. By 2035, the number of operating countries may increase by about 30%, with 10–12 new countries operating nuclear power plants (NPPs) in comparison to the current 31 countries. This growing interest requires adequate nuclear infrastructure development.

Water cooled reactors have been the predominant technology used in NPPs worldwide. The global focus on nuclear power technology development has been driven by the need to accelerate the deployment of advanced reactors, including small modular reactors (SMRs). The current trend in SMR development focuses on improving their economics, safety features and scalability. Member States' interest in floating NPPs and microreactors, as well as their applications, has increased, and several countries are currently engaged in the design development of marine-based SMRs for floating NPPs.

The use of nuclear energy for non-electric applications, including district heating, desalination and direct provision of heat for various industrial processes, is a proven technology, with 65 reactors currently in operation in several Member States, with many other Member States showing increasing interest in this option.

[1] *The total electricity production does not include Ukrainian reactor units as operational data were not submitted for the year 2023 by the time of publication.*

As regards fast reactors, the focus has been on improving safety measures by incorporating passive shutdown systems and exploring different coolants, particularly in the context of innovative reactor designs. The medium-term deployment of fast neutron systems relies on sodium cooled fast reactors as the preferred option.

Research and development in artificial intelligence (AI) implementation has demonstrated its potential to efficiently optimize core design in power and advanced nuclear reactor applications. It may also improve safety, operational efficiency and cost-effectiveness while facilitating the development of advanced nuclear technologies.

In the area of fusion energy, private sector companies are receiving growing investments as many aim to independently develop their own research and demonstration devices. At the same time, public–private partnerships in fusion are beginning to form, reflecting the overall growth in funding for fusion energy, which saw a year-on-year increase in funding totalling US $6.21 billion in 2023 (up from US $4.8 billion in 2022). The fusion industry is also becoming more geographically diverse, with 43 active companies in 12 countries. Regulatory bodies and lawmakers are also beginning to address the challenges and opportunities of fusion energy.

The ITER Council, the governing body of the ITER Organization, continued to consider revised plans for ITER that involve a change of first wall material from beryllium to tungsten. In addition, the ITER Organization continued to finalize strategies and supplier contracts for the repair of key components, while also continuing to engage with France's Nuclear Safety Authority. In 2023, researchers at the US Lawrence Livermore National Laboratory repeated at least three times the fusion energy ignition breakthrough achieved at the National Ignition Facility in December 2022.

Global forecasts from Uranium 2022: Resources, Production and Demand (Red Book 2022) indicate that uranium demand by 2030 is estimated to be between 60 960 tonnes of uranium (tU) (low-demand scenario) and 76 592 tU (high-demand scenario), and by 2040 to be between 63 040 tU (low-demand scenario) and 108 272 tU (high-demand scenario). Planned and prospective mines in 19 countries could, as they come online from 2023 to 2040, contribute to a nominal global total production capacity of 77 138 tU annually. According to the Red Book 2022, exploration and development expenditures worldwide were up slightly in 2021 by approximately US $2.8 million, following a US $2 billion drop from 2014 to 2020.

In the next decade, the nuclear fuel production industry will face increasing demand, across all nuclear fuel type segments, owing to growing construction programmes in both established and embarking countries, with ambitious objectives to develop new fuel types, including fuels for SMRs and advanced reactors. The production of low enriched uranium plus (LEU+) and, particularly, of high assay low enriched uranium (HALEU) needs to address safety and security issues, from a new licensing process and updated regulation to a specially designed supply chain infrastructure.

Spent nuclear fuel (SNF) is accumulating in storage at a rate of approximately 7000 tonnes of heavy metal (t HM) per year globally, and the stored inventory is more than 300 000 t HM. For countries with long established nuclear programmes pursuing open cycle strategies, the main challenges remain the requirement for additional SNF storage capacity and the increasing storage duration prior to disposal.

Globally, 210 nuclear reactors have been permanently retired from service. The number of facilities under active dismantling continues to increase, with a trend towards the early dismantling of facilities after permanent shutdown. Digital technologies will have an increasingly important role in advancing nuclear decommissioning, including the use of mobile robots for scanning the physical and radiological condition of structures.

The global trend towards adopting integrated radioactive waste management principles and practices helps optimize waste handling, from waste generation to disposal. Integrated waste management streamlines processes, mitigates environmental risks and fosters responsible radioactive waste management. Additionally, the growing trend in the adoption of the radioactive waste hierarchy aims to curtail the volume of radioactive waste destined for disposal facilities, leading to the preservation of these facilities as valuable long term assets.

There were 234 operational research reactors, including those in temporary shutdown, in 54 countries at the end of 2023. In addition, 11 new research reactors, including 1 accelerator driven system, were under construction in 10 countries, and 14 Member States had formal plans to construct new research reactors. The progressive ageing of the research reactor fleet worldwide has pushed operators and regulators towards adopting new techniques and methodologies to assess research reactor operating conditions for continuous safe operation.

Detailed scientific studies are dependent on how many neutrons can be produced and made available for researchers by a neutron source. Therefore, in addition to research reactors, scientists and engineers continued to develop a new generation of neutron sources based on particle accelerators and spallation target technology.

Particle accelerators have a key role in sub-cellular imaging and irradiation for cancer treatment. For the purpose of medical diagnostics, a wide range of imaging techniques such as ultrasound, computed tomography and magnetic resonance imaging are regularly used. As ion and X-ray beam manipulation techniques become increasingly sophisticated, it is possible to focus the ion or X-ray beams down to nanometre scale, allowing for novel multispectral imaging methods that can be applied in medical imaging as well as in the visualization of artefacts.

Field programmable gate arrays are increasingly used as an integral part of radiation detector data acquisition (DAQ) systems. They serve a wide range of purposes, from setting DAQ parameters and streaming/routing data, to performing advanced signal discrimination or even complete event reconstruction. Deployed data treatment algorithms are at the core of more complex functionalities, whether that be conventional or AI based.

Various Member States are investing more resources into ITER to obtain high-quality gamma interaction data. The main applications of such data are for active neutron interrogation, more precise estimates for gamma heating in the shielding of fission reactors and fusion devices and innovations in space applications.

One of the most pressing public health nutrition questions is why children in low and middle income countries (LMICs) remain short for their age despite multiple public health interventions. Environmental enteric dysfunction (EED) is increasingly common among children living in unsanitary settings in LMICs. The Agency has supported the optimization of a non-invasive breath test to measure sucrose digestion as an indicator of small intestinal function in EED that can be used across all age ranges. For more holistic results, it can be used alongside other tests to cover other aspects of EED beyond sucrose digestion.

Cervical cancer is the fourth most common cancer among women worldwide. Brachytherapy, a vital component of radiotherapy that plays a pivotal role in managing this disease, requires meticulous optimization to avoid adverse effects from under- or over-dosage. The Agency is developing a new dosimetry audit methodology to improve the quality of brachytherapy treatment. The Agency is also working to bridge the growing gap in brachytherapy education and training for LMICs, which is compounded by the technology's increasing complexity and the lack of training equipment. The Agency is using a cost-effective virtual reality tool that can overcome physical, geographical and logistical constraints to enable users to practice brachytherapy. By combining dosimetry audits and innovative education tools, the Agency is taking a comprehensive approach to enhance the capabilities of health care professionals involved in brachytherapy.

Recent advances in medical research and therapeutic strategies have ushered in a new era of hope for patients with cardiac amyloidosis. Innovative medications targeting the underlying mechanisms of amyloid deposition coupled with improved diagnostic imaging tools such as nuclear cardiology have enabled health care providers to intervene earlier and more effectively. Through advanced imaging techniques, nuclear cardiology enables the precise detection of cardiac amyloidosis and its differentiation from other cardiac disorders. The non-invasive nature of these techniques makes them particularly valuable for evaluating cardiac amyloidosis comprehensively, contributing to more timely and accurate management of the condition.

Vaccines are often a cost-effective approach to prevent livestock diseases, which can cause massive economic losses worldwide. Recently, there has been a resurgence of interest in using irradiation for vaccine production thanks to new irradiators that can provide precise radiation doses in shorter durations, and an enhanced understanding of the immune system that enables more effective assessment of vaccination responses. Technical progress has also enabled the utilization of electron beam and other irradiation methods to render pathogens inactive, allowing a shift away from the use of radioactive substances for producing irradiated vaccines.

Three billion people in agricultural regions experience high or very high levels of water scarcity, and climate change will make this worse. Cosmic ray neutron sensor technology is now being used together with high-resolution remote sensing imagery to monitor soil moisture across large areas in the landscape or at watershed level. This technology has the potential to revolutionize remote sensing for climate-smart irrigation, which would significantly improve access to baseline information for decision makers and farming communities. It also offers potential environmental research applications, such as soil moisture trend analysis, crop water productivity modelling, monitoring changes in wetland water availability and drought prediction, and providing data to support climate change adaptation policies.

Radiopharmaceuticals provide a safe and effective way to deliver radionuclides to organs, tissues or cellular targets for diagnostic or therapeutic purposes. Radiopharmaceuticals can be delivered in combination with pre-targeted approaches, chemotherapeutic combination therapies or radiation sensitizers. Pre-targeted approaches have the potential to transform theranostic strategies, enabling the use of radionuclides with short half-lives, reducing the possibility that healthy tissue is exposed to radiation. Nano-delivery systems, including theranostic nano systems, are being studied extensively, with the aim of enhancing the safety and efficacy of drugs. Nanoparticle delivery is expected to provide numerous benefits, including better therapeutic radionuclide concentration at the target with reduced side effects.

Constructed wetlands present a cost-effective and environmentally friendly alternative to conventional wastewater treatment plants, owing to their low energy consumption and simple mechanical infrastructure. They are suitable for treating all types of wastewater, including from the mining industry. Nevertheless, a better understanding of how their complex hydrodynamics work is needed to optimize treatment processes. The Agency is conducting research on the use of radiotracer technology to establish protocols and guidelines and validate flow models for constructed wetlands; to enhance the hydraulic performance of constructed wetlands for mining wastewater recovery; to optimize the efficiency of pollutant removal in constructed wetlands; and to predict a wetland's dynamic response under a variety of conditions.

Tritium is the only radioactive isotope incorporated into the water molecule, offering a valuable tracer for water cycle processes. Owing to its short half-life, tritium is mainly used to estimate groundwater recharge and assess vulnerability to pollution. As a result of the low tritium concentration in contemporary natural waters, the measurement of tritium content has become technically challenging. In order to obtain accurate and precise results for hydrological applications, significant tritium enrichment is required. The Agency has developed and extensively tested an innovative polymer electrolyte membrane system for tritium enrichment, which promises to revolutionize the ability of countries to determine the concentration of tritium in environmental water samples at ultra-low levels for both hydrological and radiological vigilance purposes.

AI is emerging as a fundamental tool in the field of microplastic identification. Despite advances in the understanding of marine plastic pollution, the quantification and characterization of microplastics remain difficult. AI's use of machine learning algorithms to unravel the complexities of degraded polymers in the marine environment represents a paradigm shift. The speed of its spectral analysis, coupled with the simulation of physical, chemical and biological processes to generate spectra of degraded polymers, position AI as a fundamental tool for improving microplastic identification.

A.

Nuclear Power

A. Nuclear Power

A.1. Nuclear Power Projections

Status

For the third successive year, the Agency has revised up its annual projections of the potential growth of nuclear power during the coming decades, confirming renewed interest in nuclear power in the context of energy security and climate change crises, as well as increased electrification demand and the need to find alternatives to fossil fuels to supply heat and hydrogen to decarbonize the industrial and transport sectors.

890 GW in 2050

In its new outlook for global nuclear capacity for electricity generation, the Agency has increased its low case projection to 458 gigawatts (GW) in 2050, representing a significant increase of 55 GW compared to the 2022 low case projection. The high case projection was increased to 890 GW in 2050, up from 873 GW in the previous year's high case projection and representing a 175 GW increase compared to the 2020 projection. To be realized, this would require large-scale implementation of long term operation (LTO) across the existing fleet, and over 600 GW of new build capacity in the coming three decades. Besides ambitious new build programmes, LTO of the existing fleet is critical to achieving the high case projections. New technological offers, including small modular reactors (SMRs) and other types of advanced reactors, can complement large reactors by providing opportunities for deploying nuclear power to meet different needs and overcome constraints (e.g. countries with small grids or off-grid applications, and non-electric applications). However, the bulk of the projected nuclear expansion is expected to be achieved with large reactors.

There are regional differences and dynamics in the way nuclear capacity is projected to evolve in both the high case and low case projections. International collaboration is key to addressing nuclear development and deployment challenges, such as the harmonization of regulatory requirements and standardization, as well as final disposal of radioactive waste. Financing is also a challenge that remains to be addressed.

Trends

There is considerable and growing interest in advanced and innovative reactor technologies, including in SMRs and their applications. While advanced large water cooled reactors are projected to represent the bulk of the nuclear capacity expansion over the next decades, SMRs are expected to play a key role in helping decarbonize hard to abate sectors as well as to provide low carbon energy in markets where they can replace fossil plants of a similar size. The nuclear sector will continue to address a number of challenges, including cost reductions, capacity building, and enhanced harmonization and standardization at the regulatory and industrial levels, to improve competitiveness and accelerate the deployment of new nuclear power capacity. To support such efforts by Member States, the Director General launched in 2022 the Nuclear Harmonization and Standardization Initiative (NHSI), which offers a unique opportunity to all nuclear stakeholders (governments, regulators and industry) to work synergically towards the common goal of the global deployment of safe and secure advanced reactors, with a focus on SMR technology.

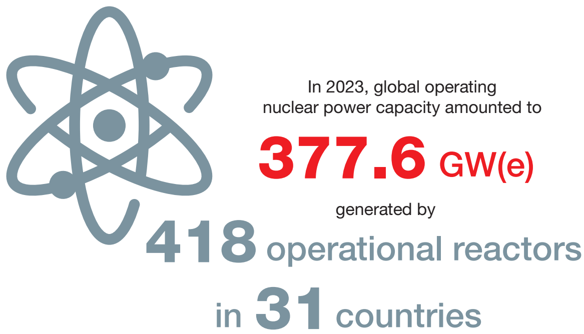
In the meantime, many countries that had decided on early nuclear phase-out are reconsidering this option and engaging in unplanned LTO.

A.2. Operating Power Plants[2]

Status

As of December 2023, the global operational nuclear power capacity was 371.5 GW(e), provided by 413 reactors across 31 Member States. Additional capacity of 21.3 GW(e) (25 reactors), which is licensed for operation, was in suspended operations during 2023. This includes 4 reactors in India, with a total net capacity of 639 MW(e) and 21 reactors in Japan with a total net capacity of 20,633 MW(e). Two reactors in Japan (Takahama-1 and Takahama-2) were restarted after being in suspended operation since 2011.

In 2023, 418 reactors with a total capacity of 377.6 GW(e) were operational, but only 403 reactors, with a combined capacity of 364.48 GW(e), reported their electricity production to the Agency. The total production of 2,515.2 TWh was reported in 2023, a slight 1% increase from 2022.[3] The three top producers were the United States of America, the biggest fleet in the world, with 30% (742.4 TWh) of the total electricity generation reported, followed by China's 16% (406.5 TWh) which continues to generate more nuclear electricity than France for 4 years and, France's 13% (323.8 TWh).

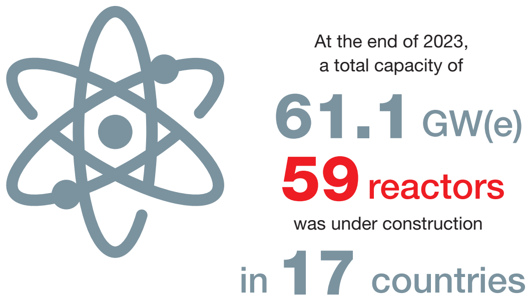


In 2023, five pressurized water reactors (PWRs) with a total capacity of 5 GW(e) were connected to the grid in five different Member States. In China, Fangchenggang-3 was connected to the grid on January 10, which is the first of two Hualong One (HPR1000) demonstration reactors being constructed at the Fangchenggang site. In Slovakia, the Mochovce-3 reactor, a VVER V-213 model with a net electric capacity of 440 MW(e), was connected to the grid on January 31. In the United States of America, the Vogtle-3 AP1000 reactor (1117 MW(e)) connected to grid on 31 March. In Belarus, Belarusian-2 reactor model VVER V-491 (1110 MW(e)) connected to the grid on 13 May. And, on 21 December, Shin-Hanul-2 (1340 MW(e)) APR-1400 reactor in Republic of Korea, connected to the grid. All these reactors, except Mochovce-3 and Shin-Hanul-2, started commercial operations during 2023.

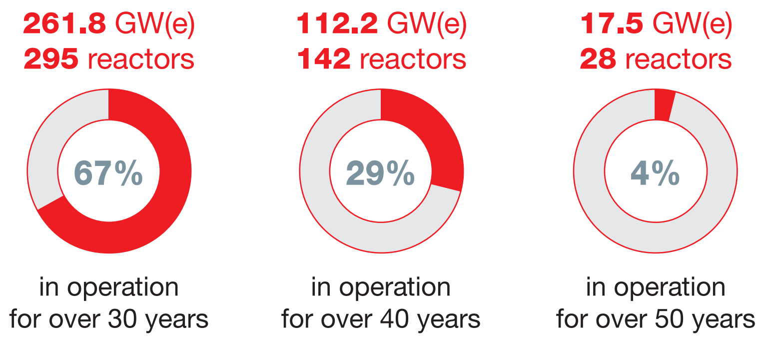
[2] Data Source: Agency's Power Reactor Information System (PRIS) (www.iaea.org/pris) as per data provided by Member States by 16 June 2024.

[3] The total electricity production does not include Ukrainian reactor units as operational data were not submitted for the year 2023 by the time of publication.

At the end of 2023, a total capacity of 61.1 GW(e) (59 reactors) was under construction in 17 countries. During the year, construction began on six PWR nuclear power reactors in China and Egypt with total capacity of 6.8 GW(e). In China, four CAP1000 reactors started construction in 2023 - Haiyang-4 (1161 MW(e)), Lianjiang-1 (1224 MW(e)), Sanmen-4 (1163 MW(e)), Xudabu-1 (1000 MW(e)), and one HPR1000 reactor unit - Lufeng-6 (1116 MW(e)). In Egypt, El Dabaa-3 (1100 MW(e)), a VVER-1200 reactor started construction on 3 May.



About 67% of global operational reactor capacity (261.8 GW(e), 295 reactors) has been in operation for over 30 years, while over 29% (112.2 GW(e), 142 reactors) has been in operation for over 40 years and 4% (17.5 GW(e), 28 reactors) for over 50 years. The ageing fleet highlights the need for new or uprated operating nuclear capacity to offset planned retirements and contribute to sustainability and global energy security and climate change objectives. Governments, utilities and other stakeholders are investing in LTO and ageing management programmes for an increasing number of reactors to ensure sustainable operation and smooth transition to new capacity.



Even as the fleet ages, operational nuclear power reactors continue to demonstrate high levels of overall reliability and performance. Load factor, also referred to as capacity factor, is the actual energy output of a reactor divided by the energy output that would be produced if it operated at its reference unit power for the entire year. A high load factor indicates good operational performance. In 2023, the global median capacity factor was 87.74%. Boiling water reactors (BWR) and pressurized water reactors (PWR) have been the best performing reactors since 2013, with median capacity factors of 89.3% and 82.7% respectively.

Throughout 2023, 6 GWe of nuclear capacity (5 reactors) were permanently taken offline. In Belgium, Tihange-2 (PWR, 1008 MW(e)) shut down on 1 February, followed by shutdown of Kuosheng-2 (BWR, 985 MW(e)) in Taiwan, China on 14 March. Germany's last three operational reactors – Emsland (PWR, 1335 MW(e)), Isar-2 (PWR, 1410 MW(e)), and Neckarwestheim-2 (PWR, 1310 MW(e))) - were shut down on April 15, twelve years after the country implemented its nuclear power phaseout policy.

Trends

Nuclear power capacity growth has been steady over the past decade, with a 20.3 GW(e) increase between 2012 and 2022. Sixty-eight reactors with 67.8 GW(e) nuclear capacity have been connected to the grid during this period. Over 83% of this capacity growth occurred in Asia, where a total capacity of 56.2 GW(e) (55 reactors) was connected to the grid. According to the reports provided to the Agency, in 2022, the nuclear power fleet generated about 2486.8 terawatt-hours (TW·h) of low-emission, dispatchable electricity.

The energy crisis in 2022 has put some decisions regarding reactor shutdowns on hold (in Belgium, Sweden and the United States of America), driving operators and regulators to implement actions to ensure safe and reliable LTO.

A.3. New or Expanding Nuclear Power Programmes

Status

There are currently some 50 countries that have an interest in adding nuclear power to their energy mix to support national socio-economic development. Among them, 27 countries are in different phases of initiating and implementing their national nuclear power programme.

Seventeen are in a decision phase — countries considering nuclear power without having made a decision (Algeria, El Salvador, Estonia, Ethiopia, Indonesia, Kazakhstan, Mongolia, Morocco, the Niger, the Philippines, Senegal, Sri Lanka, Sudan, Thailand, Tunisia, Uganda and Zambia). Most of these countries have already performed pre-feasibility studies to inform decision makers on the benefits of nuclear power as well as the needs and requirements for a successful nuclear power programme. Others have initiated their programme and are working on establishing national coordination mechanisms and developing road maps for the programme.

Ten are in a post-decision phase — countries that have decided and are building the infrastructure or have signed a contract and will start construction in the near future or have already started construction. Of these countries, Bangladesh, Egypt and Türkiye have already started the construction of their first nuclear power plant (NPP). Poland has selected the technology and signed a contract with the vendor. Ghana, Jordan, Kenya, Nigeria, Saudi Arabia and Uzbekistan have been working on preparation or evaluation of bids for their first NPP.

In Bangladesh and in Türkiye, fresh nuclear fuel for the first units was delivered on site in October 2023 and April 2023, respectively, with planned commercial operations for the first units in late 2024 in Bangladesh and in early 2025 in Türkiye. The first concrete of Egypt's El-Dabaa Unit 3 (VVER-1200) was poured in May 2023. The construction licence for El-Dabaa Unit 4 was issued by the Egyptian Nuclear and Radiological Regulatory Authority in August 2023, and site preparation for construction is ongoing. In Poland, the technology and vendor selection for the construction of PWRs with a total installed nuclear power capacity of 6000–9000 MW(e) by 2042 was completed. In Saudi Arabia, the selection of the NPP technology vendor is expected to be completed in 2025, with the first unit to be commissioned in 2036.

At the end of 2023, a total capacity of 61.1 GW(e) (59 reactors) was under construction in 17 countries, including 6 reactors with total capacity of 6.7 GW(e) that started construction during 2023. China embarked on the construction of

27 Newcomers

17 Decision-making phase

Countries considering nuclear power without having made a final decision

- Algeria
- El Salvador
- Estonia
- Ethiopia
- Indonesia
- Kazakhstan
- Mongolia
- Morocco
- Niger
- Philippines
- Senegal
- Sri Lanka
- Sudan
- Thailand
- Tunisia
- Uganda
- Zambia

10 Post-decision-making phase

Countries that have made a decision and are building the infrastructure or have signed a contract and are preparing for or started construction

- Bangladesh
- Egypt
- Ghana
- Jordan
- Kenya
- Nigeria
- Poland
- Saudi Arabia
- Türkiye
- Uzbekistan

four CAP1000 reactors (Haiyang-4, Lianjiang-1, Sanmen-4 and Xudabu-1) and of unit 6 (HPR1000) at the Lufeng nuclear power plant with a total capacity of 5.7 GW(e). In Hungary, preparations for the Paks II project to build two VVER V-527 reactors are under way. The first concrete pour for the Paks-5 reactor is scheduled for the end of 2024.

FIG. A.1. Director General Rafael Mariano Grossi met Honourable Minister Yeafesh Osman, Ministry of Science and Technology of Bangladesh, during a bilateral meeting on the margins of the 67th regular session of the General Conference in Vienna, 25 September 2023. (Source: IAEA)

Jordan is planning to issue a bid invitation specification for an SMR project for electricity production and seawater desalination in 2026. Ghana expanded its choice of reactor technology to SMRs and is currently reviewing the proposals from five potential vendors for the development of around 1000 MW(e). Commissioning is planned in 2029. Kenya has announced that it is considering the construction of a research reactor as well as both SMRs and large NPPs. In Uzbekistan, site characterization and licensing for NPPs with a total of 2400 GW(e) of installed capacity has started. The commissioning of the first NPP is planned for 2026–2030.

Estonia is only considering SMR technology for its nuclear power programme. An Integrated Nuclear Infrastructure Review (INIR) Phase 1 mission to review the status of the infrastructure was held in October 2023. The mission determined the country had developed a comprehensive assessment of its nuclear power infrastructure needs to enable the government to decide whether to launch a nuclear power programme. During the mission, the IAEA visited the public information room of Fermi Energia in Kunda, which was established to engage the local community around one of the potential sites (Fig. A.2). A Government decision about whether to proceed with the programme is expected in 2024.

FIG. A.2. The public information room of Fermi Energia in Kunda, Estonia that is used to inform the public about the potential for nuclear energy. October 2023. (Source: IAEA)

Kazakhstan selected a site for the construction of its first NPP and announced that it would hold a referendum in 2024 to decide whether to proceed with its construction. Kazakhstan also hosted an IAEA's Integrated Nuclear Infrastructure Review (INIR) Phase 1 Follow-up mission in March 2023.

Trends

By 2035, the number of operating countries may increase by about 30%, with 10–12 new countries operating NPPs in comparison to the current 31 countries. This significant increase requires the infrastructure preparedness of those countries to be stepped up, with Agency support, to ensure responsible deployment. Decision-making or the implementation of projects to build new NPPs is also progressing in many expanding countries such as Armenia, Argentina, Bulgaria, the Czech Republic, Hungary, the Islamic Republic of Iran, Pakistan, Romania and Slovakia. The nuclear industry in several Member States is also supporting the renewed interest in nuclear energy worldwide and is developing additional capacities to produce new components.

By **2035**

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operating NPPs in comparison to the current 31 countries

The technological development attracting the attention of energy planners and policymakers is the expected availability and deployment of several first-of-a-kind SMR designs by 2030. A number of countries have included SMRs in their technology considerations or continue to monitor the developments, including newcomers such as Estonia, Ghana, Indonesia, Jordan, Kenya, the Philippines, Poland, Saudi Arabia, the Sudan, Uganda and Zambia, and expanding countries such as Bulgaria, the Czech Republic, Romania and South Africa. They are driven by advances in SMR technology, and advantages that SMRs may have over large NPPs, such as lower upfront capital costs, applicability to smaller grids, non-electric applications and their modular expansion possibilities.

At the same time, Member States embarking on the development of their nuclear power programmes based on evolutionary NPPs continue to show interest in large-scale NPP technologies.

Regardless of whether a programme is based on large NPPs or SMRs, the national nuclear power infrastructure, including nuclear safety, security, and safeguards, is still needed and should be properly developed. Member States continue to report their aim of using reference designs in operation, and benefit from the experience gained by regulators and operators in the country of origin.

A.4. Nuclear Power Technology Development

Status

The global focus on nuclear power technology development is driven by the need to accelerate the deployment of advanced reactors, including SMRs. This emphasis extends beyond electricity generation to encompass non-electric applications, such as district heating, hydrogen production and desalination. There is growing interest from non-traditional stakeholders in leveraging nuclear power to decarbonize energy-intensive industrial activities. The exploration of innovative applications, such as floating NPPs for cogeneration, microreactors in remote areas and nuclear solutions for applications in outer space, reflects the dynamic evolution of nuclear technology. Advanced reactors, driven by their ability to provide flexibility to electrical grids amid the rise of variable renewable energies, are gaining traction. Furthermore, the nuclear industry is embracing artificial intelligence (AI), especially machine learning and deep learning techniques, to revolutionize operational and maintenance systems through powerful computing capabilities and data analysis tools.

Nuclear power technology is evolving with a dedicated focus on the development of advanced reactors and the broadening of their applications. Through continuous research and innovation, nuclear power is emerging as a pivotal player in addressing global energy needs while concurrently mitigating carbon emissions. Endeavours to integrate nuclear power into non-electric sectors exemplify a strategic approach aimed at maximizing the diverse benefits that nuclear technology can bring to various facets of the global energy landscape. This strategic evolution positions nuclear power as a crucial contributor to a sustainable and low carbon energy future.

Trends

Water cooled reactors (WCRs) have been the predominant technology used in NPPs worldwide. Current trends involve enhancing the safety features of WCRs, such as passive cooling systems to enhance overall system reliability, and improved fuel designs to increase fuel efficiency and reduce waste.

Owing to their compact size and potential for deployment in remote areas or regions with limited grid infrastructure, SMRs continue to be seriously considered worldwide. The current trend in SMR development focuses on improving their economics, safety features and scalability.

Current trends in fast reactor technology development focus on improving safety measures by incorporating passive shutdown systems and exploring different coolants, particularly in the context of innovative reactor designs. There is also a strong emphasis on improving the economics of fast reactors to reduce construction costs and increase fuel efficiency.

There is an increased interest in the applications of nuclear heat, for example, to power desalination plants to address water scarcity issues in many regions; to produce hydrogen through high temperature electrolysis; or in industries requiring high temperature heat, such as chemical and manufacturing sectors.

A.4.1. Advanced Water Cooled Reactors

Status

WCRs account for more than 95% of the commercial NPPs operating in the world. With their long and successful operating history, WCRs contribute significantly to global energy needs. They are widely used for power generation owing to their reliability and efficiency. The nuclear industry is continually evolving, with ongoing research and development (R&D) on advanced designs, safety enhancements and alternative technologies such as hybrid energy systems (renewables coupled to nuclear sources) to address growing energy demands and climate challenges. Advances in materials science, computational modelling and safety engineering are driving improvements in advanced WCR technologies. This includes passive safety features and systems, improved fuel technologies, more efficient cooling methods, reduced radioactive waste and enhanced proliferation resistance. For example, advanced PWR designs, such as AP1000, APR1400, EPR, HPR1000 and VVER1200, are already in operation and/or under construction in several countries. The third unit of the APR1400 at the Barakah site in the United Arab Emirates started its commercial operation in February 2023. In the United States of America, an AP1000 reactor started its commercial operation in July 2023 at Unit 3 of Plant Vogtle. In November 2023, power unit 2 of the Belarus NPP started commercial operation. In the Russian Federation, a VVER-S reactor with spectral regulation is being developed. Ongoing efforts in multiple countries are focused on further development of conceptual supercritical water cooled reactors (SCWRs) encompassing the exploration of smaller designs for diverse applications and the optimization of SCWRs to operate effectively in mixed neutron spectrum regimes. National case studies continue to be conducted on the technical and economic analysis of nuclear–renewable hybrid energy systems — especially solar and wind, which are variable sources of energy — with advanced NPPs, to provide base power load, enhance the stability of the grid and utilize nuclear heat for non-electric applications.

FIG. A.3. Vogtle Electric Generating Plant Unit 3, Georgia, USA, after completion. (Source: Southern Nuclear Co.)

Trends

There are 55 WCR units under construction in 17 Member States, of which 50 are advanced evolutionary PWRs (ACP (1), AP1000 (1), APR-1400 (3), CAP1000 (6), CAREM (1), EPR (3), HPR1000 (11), PRE KONVOI (1) and VVER (23) variants), two are advanced boiling water reactors and 3 pressurized heavy water reactors (PHWRs). These reactor designs have enhanced safety features against severe accidents and improved fuel economy. The power of these reactor units ranges from 25 MW(e) to 1630 MW(e) per unit. Most of these reactors are co-located at a single site.

In responding to climate change challenges and energy demands, many nuclear power operating countries are working on extending plant operating life, initially projected at 40 years, to as much as possible, focusing on plant modernization and enhancement of major components and equipment.

A.4.2. Small and Medium Sized or Modular Reactors and Microreactors

Status

At the end of 2023, two demonstration SMR power plants were in operation. The Akademik Lomonosov floating NPP in the Russian Federation, with two of KLT-40S reactors of 35 MW(e) each, was refuelled for the first time. The floating NPP has been in commercial operation since May 2020, supplying heat and power to the town of Pevek in the Chukotka region. In China, the demonstration High Temperature Reactor–Pebble-Bed Module at the Shidaowan site has stated commercial operation as of 6 December 2023 generating a full power of 200 MW(e), from two reactors. Three SMR power plants are in different stages of construction in 2023. In Argentina, the construction for the CAREM-25 reactor aims for 2028 as the new target date for connection to the grid. The ACP100 demonstration plant at Changjiang, Hainan province in China is under construction since July 2021. The reactor core was installed in August 2023.

The multi-purpose PWR unit, referred to as the Linglong One, will generate 125 MW(e) of electricity by 2027. The RITM-200N design has received a site licence in the Ust-Yansky district of Yakutia, Russian Federation, and is expected to generate 55 MW(e) of electricity by 2028. Manufacturing of forged blanks of various configurations for the RITM-200C reactors has started — a floating NPP with this reactor will be built in Chukotka, Russian Federation, by 2027.

Design development and licensing for near term deployment

In Canada, the construction of the BWRX-300 reactor with natural circulation is planned to begin in 2025 at the Darlington site, with connection to the grid expected by the end of 2028. The Micro Modular Reactor (MMR) design is intended for an off-grid application in Chalk River, Ontario. The vendor design review for ARC-100 is ongoing, and the licence to prepare a site is also under review. The first unit of ARC-100 will be located at the Point Lepreau site in New Brunswick.

In China, the HTR-PM (High Temperature gas-cooled Reactor Pebble-bed Module) Demo in Shidao Bay, Shandong Province of China, the world's first modular high temperature gas-cooled reactor nuclear power plant, entered commercial operation on 6 December 2023. The HTR-PM Demo project is a collaborative effort of Tsinghua University as a technical leader, responsible for R&D and main components and systems design, China Huaneng Group Co. as the owner and operator of the plant, and China National Nuclear Co. (CNNC) as the Engineering, Procurement, and Construction (EPC) contractor and the fuel manufacturer.

In France, EDF created a wholly owned subsidiary for the NUWARD project designed to develop two PWR units generating a total of 340 MW(e). In the meantime, the 'France 2030' call for projects boosts advanced modular reactor activity. In 2023, eight SMR projects were selected. They are based on several Generation IV reactor technologies, including sodium cooled fast reactor (SFR), lead cooled fast reactor (LFR), molten salt reactor and high temperature gas cooled reactor (HTGR) technology. In Europe, three nuclear regulators from the Czech Republic, Finland and France published their report on the first phase of

Fig. A.4. Director General Rafael Mariano Grossi visiting the HTR-PM (High Temperature gas-cooled Reactor Pebble-bed Module) Demo in Shidao Bay, Shandong Province of China. (Source: CAEA) the joint early review of the French NUWARD SMR, and three more regulators from the Netherlands, Poland and Sweden are set to join phase two.

In Italy, in September 2023, the Ministry of the Environment and Energy Security launched the National Platform for Sustainable Nuclear Energy, bringing together Italian nuclear stakeholders with the aim of developing a pre-feasibility study for the possible deployment of nuclear energy in the country, having SMRs, advanced modular reactors and microreactors as reference technologies.

In Japan, more than ten SMR designs developed by private sector stakeholders are under discussion. The High Temperature Engineering Test Reactor (HTTR) at the Japan Atomic Energy Agency, with a thermal power of 30 MW is operational and is utilized for the hydrogen production demonstration project.

The Republic of Korea has two notable SMR designs. The first, called SMART, is a PWR capable of generating 100 MW(e). A new partnership with Canada has been announced, with a licensing application to be submitted for the potential deployment of a SMART reactor at Chalk River Laboratories in Canada. The second, called Innovative-SMR, is an integral PWR designed to generate 170 MW(e) and is being developed by a national consortium.

In the Russian Federation, at least 20 SMR designs have been developed from different lines of technology for both land-based and marine-based NPPs for generating electricity and cogeneration. An agreement was signed for the construction of one unit of a 10-MW(e) SHELF-M reactor to power mining operations at Sovinoye. The construction of the RITM-200N, a water cooled SMR, will start in Yakutia in 2024. Two water cooled reactor projects for medium sized power plants with VVER-600 and VVER-C-600 are being developed to replace ageing VVER-440 reactors at the Kola NPP reactor site. The VVER-C-600 project features neutron spectrum regulation for fuel burnup compensation to allow operation in a closed nuclear fuel cycle.

In the United Kingdom, five SMR and advanced modular reactor designs were selected for further consideration, with contracts to be awarded in summer 2024. The designs include NUWARD, BWRX-300, ARC-100, VOYGR, and the AP300. The regulatory review began for the 470 MW(e) Rolls-Royce SMR, a standard loop-type PWR.

Numerous SMR designs are under development in the United States of America. The licensing and demonstration of the NuScale VOYGR design, which could comprise six modules that generate 77 MW(e) each, has shifted from Idaho Falls to other potential users in the USA and Europe, including Romania. The two Generation IV reactor technologies are TerraPower's Natrium SFR and the Xe-100, which uses HTGR technology. Other advanced designs include the Kairos Power fluoride salt cooled high temperature reactor, eVinci microreactor and the Holtec SMR-160. The Microreactors Applications, Research, Validation and Evaluation (MARVEL) project is also ongoing.

Trends

Throughout 2023, Member States' interest in floating NPPs and microreactors, as well as their applications, increased. Significant industrial and regulatory efforts are ongoing to facilitate their design development and early deployment. Technology of higher maturity or readiness level has prospects for early

FIG. A.5. Director General Rafael Mariano Grossi at the opening of the International Symposium on the Deployment of Floating Nuclear Power Plants — Benefits and Challenges, held at the Agency's Headquarters in Vienna, November 2023. (Source: IAEA)

deployment, around 2030. In 2023, technology development activities for a subset of SMRs, known as microreactors, continued in Canada, the Czech Republic, Japan, the Russian Federation, the United Kingdom and the United States of America. Designed to generate a lower range of power up to 20 MW(e), microreactors are envisioned as the optimum solution for providing cogeneration of heat and electricity in remote regions or small islands, and/or to replace diesel generators. High temperature reactor, fast reactor and heat pipe are among technologies adopted for microreactors.

More countries are currently engaged in the design development of marine-based SMRs for floating NPPs for on-shore and offshore applications. A reactor design start-up company in Denmark is developing the Compact Molten Salt Reactor to produce 100 MW(e). The Republic of Korea continues the development of BANDI-60, a PWR-based floating power unit to generate 60MW(e). The Russian Federation has adopted the RITM-200M design for upcoming floating NPPs. Floating NPPs with SMRs are designed for niche markets, including distributed power generation and heat supplies to remote communities, desalination and hybrid energy systems through collaboration with marine and shipbuilding industries. Legal, regulatory and institutional aspects of these transportable SMR concepts are being analysed and assessed to facilitate deployment.

In this fast-developing scenario, the IAEA Platform on Small Modular Reactors and their Applications, established in 2021 by the Director General, coordinates the Agency's activities in the field of SMRs, provides a focal point for Member States and other stakeholders to request assistance on general issues related to SMRs and their applications through official channels and serves as the mechanism by which the IAEA responds to these requests. Among the key collaborative efforts in 2023 through the mechanism of platform it is worth to note the expert mission to review a feasibility study on desalination with SMRs in Jordan and the International Symposium on Floating Nuclear Power Plants.

A.4.3. Fast Reactors

Status

As of December 2023, there were five SFRs in operation in three Member States, including three in the Russian Federation, one in China and one in India. In 2023, the Russian BN-800 reactor was transferred to full loading with MOX fuel, which marks the first stage of closing the nuclear fuel cycle. The Prototype Fast Breeder Reactor, an experimental industrial-sized SFR with a capacity of 500 MW(e), is currently under commissioning in India. It is expected to be connected to the grid in 2024. China is currently building two identical CFR-600 demonstration reactor units, with the first one already under commissioning. The experimental fast reactor Joyo will restart in 2026 following improvement works. Heavy liquid metal coolant technology is attracting increasing attention, especially in the area of fast neutron SMRs. The Russian Federation is constructing a 300 MW(e) demonstration LFR, BREST-OD-300, while several LFR designs are in development in China, the United Kingdom and the United States of America, as well as the European Union. Out of the six innovative reactor concepts developed by the Generation IV International Forum, three — sodium, heavy liquid metal and helium cooled — are fast neutron systems. The remaining two — molten salt and supercritical water cooled — have the capability to operate in either fast or moderate neutron spectrums.

FIG. A.6. TVEL Fuel Company dispatches fuel to China for the core loading of the first CFR-600 fast neutron reactor. (Source: TVEL)

Trends

The medium-term deployment of fast neutron systems relies on SFRs as the primary option. In addition to the three SFRs operating in the country, the Russian Federation is developing the large 1200 MW(e) BN-1200 reactor and constructing the Multipurpose Fast Research Reactor (MBIR). China is working on the development of a 1 GW(e) CFR-1000 Generation IV reactor. TerraPower, a company based in the United States of America, is developing the Natrium SFR, which operates in connection with molten salt storage. This advanced technology has the capability to reach a peak power of 500 MW(e), making it a potential replacement for typical coal power plants and can be integrated with other renewable energy sources. Another US SFR project, the Versatile Test Reactor, is awaiting US Congress approval. In France, amongst the 15 projects included in the call for projects 'France 2030', seven companies were selected for the development of fast neutron SMRs in 2023. Four spin-off fast neutron SMR projects were initiated in 2023. While SFRs remain the most mature technology, several countries are constructing and developing LFRs, such as the BREST-300, which is currently under construction in the Russian Federation and expected to be commissioned in 2028. The joint United Kingdom–United States of America 450 MW(e) Westinghouse LFR, joint Italy–Romania 120 MW(e) Advanced Lead Fast Reactor European Demonstrator, and several SMR-type LFR designs in China and in France are also being developed. Start-up companies are working on the development of the 55 MW(e) SEALER in Sweden, as well as the LFR-AS-30 (30 MW(e)) in France and the LFR-AS-200 (200 MW(e)) in the United Kingdom, with R&D also being developed in Italy. Other fast neutron spectrum reactor technologies, such as gas cooled fast reactors and molten salt fast reactors, are under development in the European Union and the United States of America.

A.4.4. Non-electric Applications of Nuclear Power

Status

The use of nuclear energy for non-electric applications, including district heating, desalination and direct provision of heat for various industrial process is a proven technology, with about 70 reactors currently in operation in several Member States, with many other Member States showing increasing interest in this option.

In 2023, 45 nuclear power reactors across 10 Member States supplied 2046.0 GWh of electrical equivalent of heat for non-electric applications. The majority of this heat (88%) was utilized for district heating, totalling 1799.1 GWh, in Russia, China, Slovakia, the Czech Republic, Switzerland, Romania, Hungary, and Bulgaria. Industrial heating in India and Switzerland was supported by 211.8 GWh (10%), while 35.1 GWh (2%) was used for desalination.

China has recently started a major programme to deploy nuclear district heating on a large scale, joining a group of existing users, including Bulgaria, the Czech Republic, Hungary, Romania, the Russian Federation, Slovakia, Switzerland and Ukraine. China started the Hongyanhe project in 2022, following the launch in 2021 of a district heating demonstration project at the Qinshan NPP in Zhejiang province. In addition, other countries that already have extensive district heating networks in place, such as Finland and Poland, are considering the use of nuclear heat to repower those networks with zero emission nuclear energy.

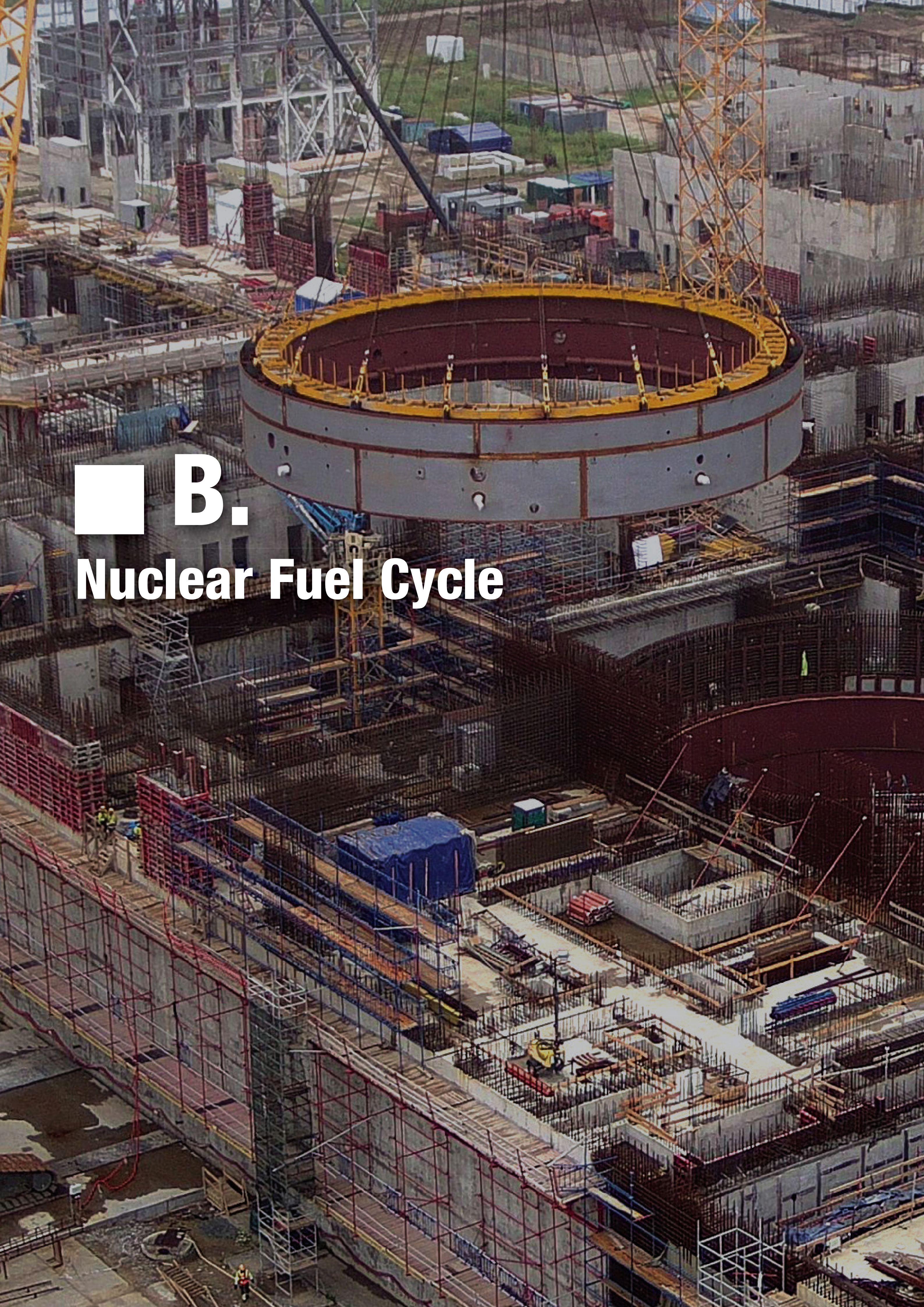
Nuclear-powered desalination is attracting increasing interest in Member States, as the use of desalination is growing rapidly worldwide, in order to provide essential access to clean water to a growing share of the global population. India is planning a substantial expansion of its nuclear desalination capabilities, with plans to install two multi-effect distillation units capable of processing 1000 cubic metres per day, powered with nuclear heat, at Kalpakkam. Other countries (Japan and the United States of America) are utilizing nuclear electricity to power reverse osmosis units for desalination, while Kazakhstan and Pakistan have experience with thermal nuclear desalination, and China plans to install reverse osmosis units powered by nuclear energy.

Several Member States have expressed interest in hydrogen production using nuclear energy, including Canada, China, France, Japan, the Republic of Korea, the Russian Federation, Sweden, the United Kingdom and the United States of America. In the latter, the Nine Mile Point Nuclear Station started hydrogen production in 2023 utilizing low temperature electrolysis, joining the Oskarshamn NPP in Sweden, which started commercial hydrogen production in 2022. In addition, both the United Kingdom (Heysham NPP) and the United States of America (Prairie Island NPP) are in the development phase of projects to connect existing NPPs to high temperature electrolysers, utilizing steam extracted from NPP secondary loops to increase the efficiency of hydrogen production. In the Russian Federation, Rosenergoatom is conducting an environmental impact assessment of a project for the construction of a pilot complex for hydrogen production at Kola NPP. Several other coupling projects of nuclear reactors with low temperature electrolysers are in the development phase, including in France, the Russian Federation and the United States of America.

FIG. A.7. The Nine Mile Point Clean Energy Center started commercial nuclear hydrogen production in 2023. (Source: Constellation)

Trends

Nuclear energy is unique among various low carbon sources in its capability to supply both heat and electricity around the clock, at scale, with no geographical limitations, and in a dependable and dispatchable manner. This unique combination of advantages is driving increased interest in the potential of nuclear energy to help decarbonize not only the electricity sector, but also other energy applications, which, being currently powered with fossil fuels, generate the majority of the carbon emissions worldwide. These sectors include heating, transportation and various industrial applications, from cement to oil and gas production, iron making, fertilizer production and a vast array of other chemicals. Nuclear energy can provide zero carbon electricity where electrification is practical, supply zero carbon heat directly in order to replace the combustion of fossil fuels, and provide decarbonized energy for hydrogen production, which is increasingly seen by Member States as a key enabler to a low carbon economy. Such applications are increasingly appealing, as many regions of the world are experiencing historically high costs of fossil fuels, as concerns about security of energy supply are growing in prominence globally, and Member States are ramping up their efforts to fight climate change.



B.

Nuclear Fuel Cycle

B. Nuclear Fuel Cycle

B.1. Front End

Status

As of 30 October 2023, the uranium (U) spot price was US $74.00/lb U_3O_8 (US $192.38/kg U), a 16-year high. This is a dramatic change from the relatively flat 2016-2021 market prices of about US $20–$30/lb U_3O_8 (US $52–$78/kg U), which amounts to an increase of around 200%.

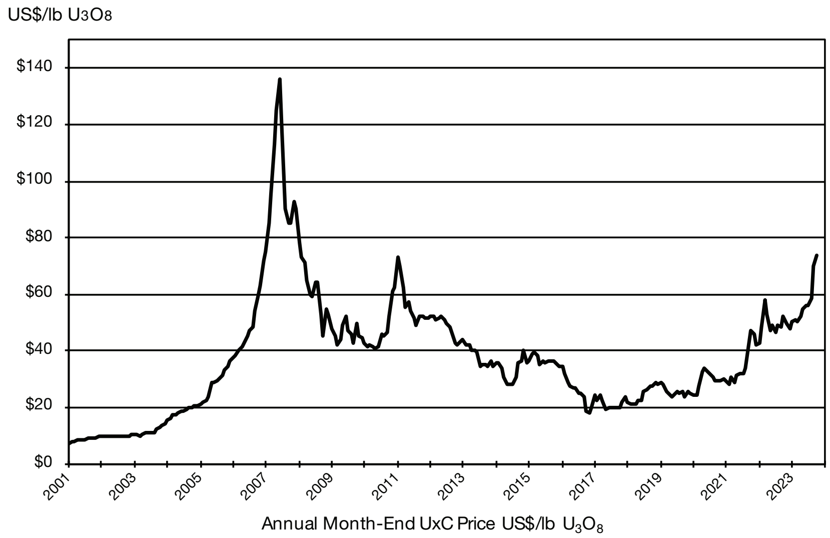
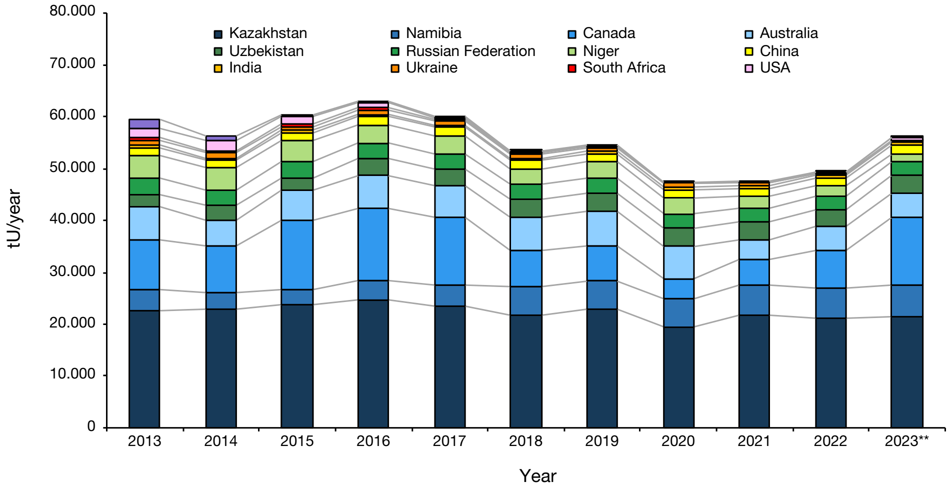


FIG. B.1. 2001–2023 uranium spot price evolution (up to October 2023; data source: UxC)

The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA)–IAEA joint publication Uranium 2022: Resources, Production and Demand (Red Book 2022), covering 2019 and 2020, reported that global uranium mine production had decreased by 13%, from 54 478 tonnes of uranium (tU) to 47 342 tU. Major producing countries, including Canada and Kazakhstan, had limited total production in recent years in response to the pre- to mid-2021 sustained depressed uranium market. Furthermore, uranium production cuts had been unexpectedly deepened owing to the global COVID-19 pandemic in 2020–2021.

The Red Book 2022 reports that, as of 1 January 2021, total production capacity of idled mines amounts to an additional 29 410 tU annually, and at least an additional 335 000 tonnes of in-ground recoverable uranium resources are available. These operations, which have all the necessary licences, permits and agreements for operation and have produced commercially in the past, could potentially be brought back into production relatively rapidly (within a year or two). Preliminary data for the Red Book 2024 indicates, however, that uranium production has rebounded, up slightly to 47 504 tU in 2021, to 49 336 tU in 2022, and to 56 143 tU in 2023, which was the average over the decade preceding the COVID-19 pandemic. In 2023, the four highest annual uranium producing countries — Australia, Canada, Kazakhstan and Namibia — are estimated to have increased production by about 2%, 76%, 1% and 7%, respectively over 2022 production rates.



“Others” include the remaining small producers.

** OECD/NEA–IAEA estimate.

FIG. B.2. Evolution of global uranium production, 2013–2023.

Global identified recoverable conventional uranium resources (i.e. those that are reasonably assured and inferred to exist in geologic deposit types that are typically mined) are adequate to support near- and mid-term growth in nuclear generating capacity. The Red Book 2022 reports that over 6 million tonnes of identified uranium resources are recoverable at today’s market prices, which, considering the global reactor-related uranium requirements for 2020 of 60 114 tU, is sufficient for over 100 years.

Historically, the gap in primary uranium supplies has been met by secondary supplies. However, this has been decreasing and is forecast to continue declining to 2040. With the recent sustained and increasing uranium market spot price, the uranium production industry has been reinvigorated, and a few primary producers have restarted their operations that were idled and placed under care and maintenance owing to the prolonged period of low uranium spot prices. These operations include the Honeymoon mine in Australia, the McArthur River mine and the Key Lake mill in Canada, and the Smith Ranch–Highland operations in the United States of America, all of which will have resumed production between 2022 and 2024, as well as the Langer Heinrich mine in Namibia, which is expected to restart in 2025.

According to the Red Book 2022, exploration and development expenditures worldwide were up slightly in 2021 to nearly $280 million, a 10% increase from 2020. This followed a $1.88 billion drop from 2014 to 2020. Preliminary data for the Red Book 2024 indicates that expenditures are expected to have continued rising significantly in 2022 and 2023. An expanded exploration programme, for example, was announced in 2023 by NexGen Energy near the Arrow deposit in the Athabasca Basin in Canada.

The fuel production market has historically been characterized by strong competition among fuel manufacturers and suppliers. Currently, the fuel production capacity exceeds the needs, at both global and regional levels.

Nuclear fuel production is a mature technology that has continuously progressed over the years through fabrication process automation and digitalization, reduction of operational waste and enhancement of radiation protection for workers. In parallel, progress has been made in many countries to improve both nuclear reactors’ economics, through increasing fuel burnups and extending fuel cycle duration, and nuclear fuels' operational reliability, by reducing fuel failure occurrences.

Some Member States intend to increase the use of reprocessed uranium and uranium–plutonium based fuels in light water reactors (LWRs) to optimize the use of natural fissile resources. Several Member States, including France, India, Japan and the Russian Federation, aim to use uranium–plutonium mixed fuels in fast reactors. Some Member States, operating PHWRs, have started replacing natural uranium-based cores with slightly enriched uranium cores to improve the competitiveness of their reactors.

Several Member States, including Belgium, Canada, China, France, Japan, the Republic of Korea, the Russian Federation, Spain and the United States of America, have ongoing research, development and demonstration programmes to deploy accident tolerant fuels (ATFs) in current reactor fleets through lead test rods and lead test assembly fabrication, irradiation and post-irradiation examinations, fuel performance assessment, system thermal hydraulics, and severe accident code development and validation. ATFs incorporate new materials, and some of their designs should enable longer and more effective operations in reactors by extending the time between refuelling outages up to two years, thereby improving NPP economics. Some Member States are developing advanced manufacturing technologies, such as additive manufacturing (e.g. with three-dimensional printers), or use of AI and fully automatized fuel manufacturing processes to deploy innovative and doped fuels on the market.

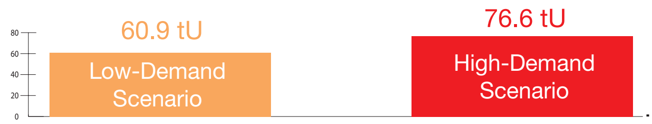
Some SMR designs will use conventional fuel designs (similar to the low enriched fuel designs commonly used in large-scale reactors). Other SMR developers have chosen more innovative fuel designs, based on HALEU for instance, to reap benefits beyond those achievable with conventional fuel designs. R&D is under way on uranium dioxide and uranium–plutonium mixed oxide fuels and ATFs for light/heavy water cooled SMRs; cermet fuel for floating and land-based light water cooled SMRs; tristructural isotropic fuels for high temperature gas/molten salt/heat pipe cooled SMRs; metal or ceramic fuels for liquid metal/gas/heat pipe cooled fast SMRs; and molten salt fuels for molten salt cooled SMRs. However, such designs will require separate or completely new fuel fabrication plants and supply chains. The qualification and licensing of these innovative fuel designs, especially those with higher enrichment levels (e.g. LEU+ and HALEU), will also be necessary before their industrial deployment.

Trends

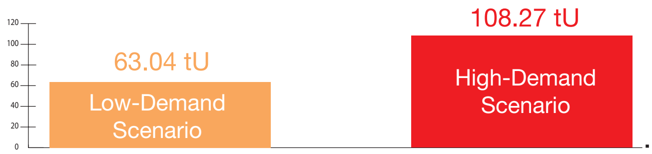
During the United Nations Climate Change Conference COP28, 22 countries made a declaration to advance the aspirational goal of tripling nuclear power capacity by 2050. Global forecasts from the Red Book 2022 indicate that uranium demand by 2030 is estimated to be between 60 960 tU (low-demand scenario) and 76 592 tU (high-demand scenario), and by 2040 to be between 63 040 tU (low-demand scenario) and 108 272 tU (high-demand scenario). Nevertheless, if there is an increase in uranium demand due to the introduction of SMRs as reported in the World Nuclear Association's Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2023–2040, world annual uranium requirements could range from 86 914 tU (low-demand scenario) to as high as 184 316 tU (high-demand scenario) by 2040.

Planned and prospective mines in 19 countries could, as they come online from 2023 through 2040, contribute to a nominal global total production capacity of 77 138 tU annually. The assurance of uranium supply will require that the idled mines come back online and that the planned and prospective mines be realized, and the discovery of new deposits will require sustained favourable market conditions. This is particularly important for the development of new uranium mines, which take on average 10–15 years to be developed, from deposit discovery to mining operations. Also, significant timely investment in exploration and mining/processing technology will be required, including cost-effective uranium extraction techniques for exploiting unconventional deposit types (e.g. uranium from phosphate and black shale deposits).

Red Book 2022 Forecast



Uranium Demand in 2030



Uranium Demand in 2040

Relatively recent innovations and developments that can advance sub-economic and marginal uranium deposits into producing mines include in-situ recovery of uranium from unconformity-type deposits, as demonstrated at the Phoenix deposit in the Athabasca Basin in Canada; the in-situ bioleaching of sandstone-type uranium deposits, such as at the 512 uranium deposit in China, where field experiments are being carried out; the up-grading of the beneficiation of low grade uranium ores, as is being developed at the Marenica calcrete-type deposit in Namibia; and Surface Access Borehole Resource Extraction, a new innovative and scalable mining method that can allow for the exploitation of relatively small high grade orebodies that are either too small or too deep to be mined economically by open-pit or underground mining methods. In addition, heap leaching techniques, which are typically used to extract metals from other types of mineral deposits, are showing promise for some uranium operations.

A nuclear fuel assembly is not a fungible commodity but a complex product incorporating design, licensing, and R&D activities, and needs to meet certain specifications. These are determined by the physical characteristics of the reactor, by the reactor operating and fuel cycle management strategy of the utility, and by national or regional licensing requirements. New developments in fuel design and fabrication technologies can be divided into two main areas: evolutionary or revolutionary fuels developed for existing reactor fleets, which can offer improvements in terms of safety and performance, as well as operating economics and waste management; and evolutionary or revolutionary fuels developed for advanced reactors, including for SMRs.

Some Member States have already planned to develop licensing infrastructures to support the extension of fuel burnups and enrichments beyond the 5% legacy limit by the mid-2020s, and to enable the safe and economical operation of 24-month cycles in existing LWRs without physically changing the manufacturing plants and transport containers (i.e., only through changes in licensing procedures).

In the next decade, however, the nuclear fuel production industry will face increasing demand, across all nuclear fuel type segments, owing to growing construction programmes in both established and embarking countries, with ambitious objectives to develop new fuel types, including fuels for SMRs and advanced reactors. Many different ATF designs are being explored, resulting in a large variety of solutions with different levels of complexity; some ATF designs are relatively easy to fabricate using existing fabrication lines and facilities, while others will require the setting up of new fabrication lines and facilities. Enhanced ATFs and innovative nuclear fuel designs will need enrichments above 5% (LEU+ and HALEU will be required to manufacture many of the innovative concept fuels). The successful deployment of all types of SMR fuels will require the maturity of fuel production technologies from the R&D stage to the industrialization stage.

The development of new LEU+/HALEU-certified transport packages is crucial for LEU+/HALEU fuel utilization. Currently, HALEU programmes are being considered in North America and the Russian Federation. The Russian State Atomic Energy Corporation “Rosatom” has the technological capability to produce both LEU+ and HALEU enriched up to 19.75% in U-235, in various forms. In most countries, the current nuclear fuel cycle infrastructure is limited by regulation to 5% U-235 enrichment. However, in the next decade, the demand for HALEU may change quite significantly owing to the mass deployment of SMRs, with many of these new reactor designs requiring either LEU+ or HALEU. In the United States of America, Centrus Energy began demonstrating HALEU production in October 2023 and will expand the production incrementally, as the demand for HALEU grows. URENCO has announced its readiness to supply LEU+ fuel for international markets, is exploring the construction of a dedicated HALEU unit, and signed a consortium agreement with Orano to develop cylinders for LEU+/ HALEU fuel transport.

B.2. Back End

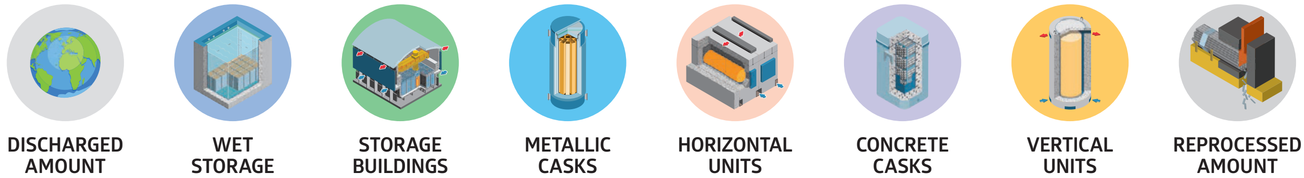
Status

Spent nuclear fuel (SNF) is accumulating in storage at a rate of approximately 7000 tonnes of heavy metal (t HM) per year globally, and the stored inventory is more than 300 000 t HM. For countries with long established nuclear programmes pursuing open cycle strategies, the main challenges remain the requirement for additional SNF storage capacity and the increasing storage duration prior to disposal. In some countries, SNF is moved from wet to dry storage facilities after an initial cooling time. New dry storage facilities have started operation (e.g. in Argentina, Slovakia and Slovenia) or are planned (e.g. in Japan). The US Department of Energy has started an initiative for a consent-based siting approach for one or more federal consolidated interim storage facilities.

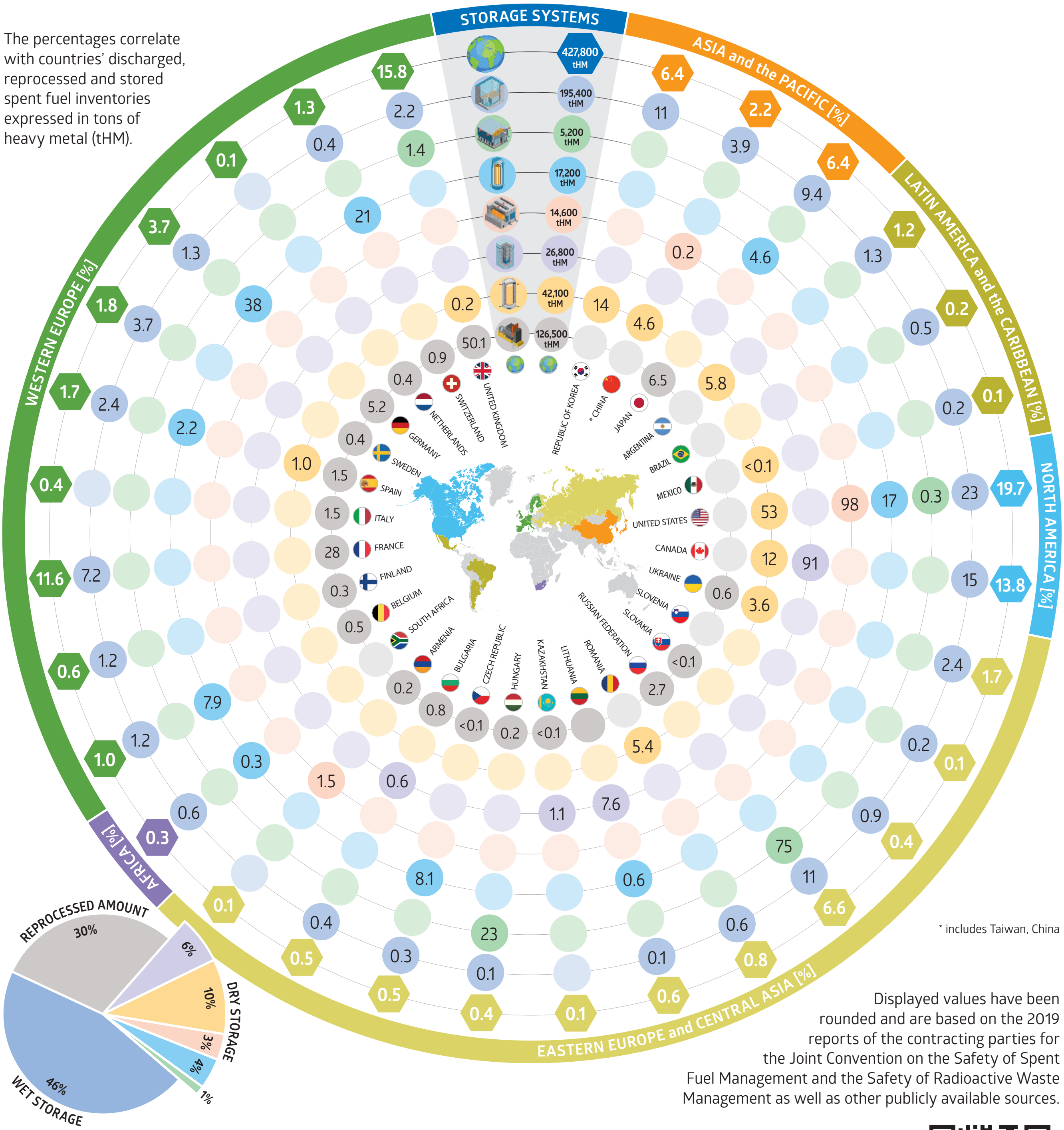
Member States are continuing with the removal and relocation of SNF in the framework of the decommissioning projects of their NPPs. New technologies have been deployed to improve inspection technologies, mainly new robotic platforms used for inspection tools, for SNF storage systems. SNF transportation is a routine operation in some countries. In recent years, new packages for storage and transportation have been developed, licensed, and put into operation to accommodate new or expanding inventories.

The lifetime extensions of some NPPs are contributing to an increase in the amount of SNF to be stored. A significant reduction in global reprocessing capacity occurred after the closing of reprocessing plants in the United

SPENT FUEL MANAGEMENT
THE INVENTORY STATUS



The percentages correlate with countries' discharged, reprocessed and stored spent fuel inventories expressed in tons of heavy metal (tHM).



* includes Taiwan, China

Displayed values have been rounded and are based on the 2019 reports of the contracting parties for the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management as well as other publicly available sources.

Read more

FIG. B.3. SNF storage systems used worldwide.

Kingdom. Development at commercial scale of new recycling technologies for the current fleet and advanced reactors' fuels continues in France, India, Japan and the Russian Federation. Japan expects the Rokkasho Reprocessing Plant to begin commercial operation in 2024. In the United States of America, Oklo has submitted a plan outlining the pre-application engagement for a commercial-scale reprocessing plant to the US Nuclear Regulatory Commission (NRC). The Russian Federation is modernizing the RT-1 and ODC reprocessing plants at the Mayak Production Association to increase its SNF reprocessing capacity and improve operational efficiency.

Trends

Understanding the behaviour of SNF in various storage systems, as well as the ageing and degradation mechanisms of storage structures, systems and components, remains vital to ensure that SNF can continue to be stored safely and subsequently transported to disposal or reprocessing facilities. As spent fuel disposal programmes are progressing and approaching the final stages of construction in some Member States, there has been an increase in the number of preparation activities, such as the development of characterization programmes. Continuation of such efforts is particularly important when considering that greater reactor efficiencies have been achieved through the production of spent fuel with higher initial enrichments and higher burnups, leading to increases in thermal outputs and potentially higher risks of cladding embrittlement that may impact subsequent spent fuel management steps.

As new fuel designs for both the existing fleet of reactors (e.g. doped fuels) and advanced reactor designs (including SMRs), which may lead to potentially different behaviours in spent fuel management, are envisaged, innovative spent fuel management solutions will need to be sought to allow for their timely deployment. The Agency coordinates international research activities on this matter to foster information sharing and enhance knowledge and capacity building in Member States through the collection of operational experiences, research findings, and policy and strategy approaches.

Despite an overall reduction in global spent fuel reprocessing capacity, there is increasing interest in the development of advanced recycling technologies, both for current fuels and to support the deployment and sustainability of advanced reactors and SMRs. Integration of new and innovative fuel cycles with existing fuel cycles is an important undertaking to address current energy supply challenges and ensure the sustainable, safe and secure development of nuclear power. While already implemented in some countries, initiatives to address spent fuel and radioactive waste management in an integrated manner are starting to be discussed and developed in other countries. Deployment of new reactors and associated fuel cycles will be a major challenge and, therefore, international collaboration and partnership will be paramount for success.

C.

Decommissioning, Environmental Remediation and Radioactive Waste Management

C. Decommissioning, Environmental Remediation and Radioactive Waste Management

C.1. Decommissioning

Status

Globally, 210 nuclear reactors have been permanently retired from service, of which 23 have been fully decommissioned.[4] These shutdown reactors are located in 21 countries across Europe, Asia and North America. Over two thirds of shutdown reactors, both decommissioned reactors and reactors under decommissioning, are concentrated in 5 countries, namely France (14), Germany (33), Japan (27), the United Kingdom (36) and the United States of America (41). Accordingly, these countries have the largest ongoing power reactor decommissioning programmes, although several other countries, including Bulgaria, Canada, Italy, the Republic of Korea, Lithuania, the Russian Federation, Slovakia, Spain and Sweden, as well as Taiwan, China, also have power reactor decommissioning projects under way.

nuclear reactors have been permanently retired from service

Major decommissioning developments in 2023 have included the final shutdown of five power reactors worldwide, including Germany's last remaining power reactors (Emsland, Isar-2 and Neckarwestheim-2), a power reactor in Belgium (Tihange-2) and a boiling water reactor in Taiwan, China (Kuosheng-2). This rate of shutdown is in keeping with the past decade's average. There remains a strong interest among operators to extend the lifetimes of reactors built in the 1980s to 60 years or more.

Significant experience continues to be gained from the decommissioning of research reactors, of which approximately 450 have been fully decommissioned around the world. Currently, 67 research reactors are under decommissioning.

Major decommissioning works are also proceeding at fuel cycle facilities around the world, including several sites in France, the Russian Federation, the United Kingdom and the United States of America.

Significant technical progress was achieved under several ongoing decommissioning projects, including Enresa's completion of restoration work at the retired José Cabrera NPP site. The NPP is the first to be fully dismantled in Spain (Fig. C.1).

In addition, the operator of Brennilis NPP obtained a decree from the French Government in September 2023 that authorized the completion of the facility's dismantling. This decree paves the way for complete dismantling works at the reactor building, the renovation of civil engineering structures, the demolition of remaining surplus components and the final remediation of the site.

[4] As per PRIS database (pris.iaea.org/pris/home.aspx) as of 31 December 2023, extracted on 6 June 2024.

FIG. C.1. The José Cabrera NPP site's former containment building. (Source: Enresa)

Significant achievements were made within the Japan Atomic Energy Agency's back-end programme. For example, the Monju reactor, a fast breeder reactor, entered the second phase of its decommissioning, which includes preparation for the dismantling of the sodium-related component (e.g. neutron shielding) and the electricity generation component (e.g. turbine), as well as approval from the regulatory authority, which was obtained in February 2023.

In October 2023, Rosenergoatom received a licence from the Federal Environmental, Industrial and Nuclear Supervision Service for the right to decommission power units 1 and 2 of the Novovoronezh NPP. The planned project completion date is 2035.

FIG. C.2. Dismantling a high-pressure feedwater heater as part of the decommissioning of the Monju reactor. (Source: JAEA)

Trends

Despite the uncertainty surrounding the future rate of facility shutdowns, the number of facilities under active dismantling continues to increase, with a trend towards the early dismantling of facilities after permanent shutdown. Factors influencing this trend include government policies, the desire among facility owners to minimize costs associated with facility upkeep over long periods and uncertainty surrounding the cost of eventual dismantling and associated material management.

There is an increased emphasis on applying circular economy principles to decommissioning projects. Sustainability in decommissioning is manifested at various levels, including a more effective use of decommissioning materials as an attempt to minimize waste that requires final disposal and a greater consideration of reusing/repurposing sites or facilities to support future industrial projects. However, a circular economy requires collaboration among diverse stakeholders, from policy developers and regulators to communities, who may have varied perspectives and expectations regarding the acceptance of radioactivity in their daily lives.

Looking ahead, digital technologies will have an increasingly important role in advancing nuclear decommissioning. Important benefits include efficiency and the optimal use of available human, financial and technological resources; radiation safety to minimize exposure of the workforce; regulatory processes and stakeholder engagement to facilitate understanding of decommissioning activities; and knowledge management for effective transfer of knowledge and experience between current and future workforces.

Other developments that are closely associated with the growing adoption of digitalization are the use of mobile robots for scanning the physical and radiological condition of structures and the use of remotely operated tools for waste treatment, packaging operations and operations in areas that are difficult to access, e.g. owing to high dose rates.

Digital technologies will bring many more potential benefits to the nuclear industry as a whole, making it significantly easier for experience gained from ongoing decommissioning projects to be made available to nuclear facility designers, operators and regulators, as well as to various stakeholders in future decommissioning projects.

C.2. Environmental Remediation and Management of Naturally Occurring Radioactive Material

Environmental Remediation

Environmental remediation activities are mostly focused on four types of contaminated sites, namely nuclear sites (eventually as part of a decommissioning project); former uranium mining and processing sites; sites affected by radiological accidents; and those where non-nuclear industry operations have taken place and left behind residues/wastes that need to be properly managed (e.g. Fig. C.3).

In 2023, steady remediation progress continued across the world. In the United Kingdom, the Nuclear Decommissioning Authority, initially responsible for the cleanup of the country’s 17 oldest civil nuclear sites, expanded its work programme to include the advanced gas cooled reactor fleet. In the United States of America, 91 of the 107 sites in the country successfully treated their contaminated water and soil. Over 179 000 containers of transuranic waste were permanently disposed of. By the end of 2023, 17 000 acres of land had been released. In Washington State, the Hanford Site’s B reactor, now part of the Manhattan Project National Park along with Oak Ridge National Laboratory and Los Alamos National Laboratory, completed critical activities in tank water treatment and reduced risk by upgrading and improving facilities. Existing cleanup efforts are ongoing at 16 sites, although cleanup at these remaining sites is relatively difficult owing to the unique characteristics of the radioactive waste present.

FIG. C.3. Temporary Storage of NORM residues. (Source: IAEA)

Management of Naturally Occurring Radioactive Material

In addition to radioactive waste, many countries also face the challenge of dealing with large amounts of residues containing varying levels of natural radionuclides (NORM) generated from non-nuclear operations.

Phosphogypsum, a calcium sulphate by-product of fertilizer production, is generated at large volumes. As transportation and long term storage entail investment and operating costs, phosphogypsum is often left in open waste dumps, many located in open areas. The adverse environmental impact of phosphogypsum dumps is often manifested in the contamination of groundwater, surface water and soil.

Phosphogypsum contains rare earth elements iron, titanium, magnesium, aluminium and manganese, but also toxic heavy metals. Many of the rare earth elements are listed as ‘critical’ raw materials in the European Union. Phosphogypsum also has different potential uses, including road base application that is both cheaper and as effective as current road base materials, if not more so; agricultural soil amendment that provides much-needed sulphur to the soil; and fill cover to speed up the degradation of waste and extend the life of a landfill; as a material to make ceramic roofing tiles; and as a material for marine substrates, such as oyster cultch. Through pursuing similar approaches, residues from other operations can be valorized, and profits made through the sale of these materials can be reinvested in the remediation of contaminated sites. This approach represents a potential solution, particularly in the case of low-income Member States that would otherwise not have the necessary resources to remediate such sites.

Trends

Environmental Remediation

While efforts to remediate contaminated sites continued worldwide, the trend of going beyond risk reduction to an expansive perspective of value aggregation, without compromising safety, gains momentum in the remediation community. The principles of a circular economy entail a focus on the re-valorization of the site at the end of both nuclear and non-nuclear operations. Successful remediation works will play crucial role to ensure that nuclear power can contribute to alleviate the impacts of climate change. In that direction, sustainable and resilient remediation solutions are needed taking into consideration active participatory decision-making processes.

Management of Naturally Occurring Radioactive Material

Many countries have demonstrated how NORM residues can be minimized through the adoption of circular economy approaches (e.g. Spain used phosphogypsum as a soil amendment and the Netherlands used NORM residues as stabilizers in landfills). Critical materials can be extracted from NORM residues and innovative techniques are needed in these cases. Governmental policies that promote the adoption of circularity approaches will be mostly needed backed up by regulations that need to be adapted to a circular economy scenario.

C.3. Radioactive Waste Management

Status

Throughout 2023, several countries made significant progress on the management of radioactive waste, reaffirming their dedication to responsible waste handling and disposal and their commitment to safer and more sustainable waste management practices.

Member States with decades of experience in the implementation of waste management solutions have further progressed some of their main national programmes. For example, France’s National Radioactive Waste Management Agency (Andra) submitted a license application to construct its geological disposal facility under the Cigéo project in January 2023. In addition, in anticipation of future waste arisings from NPP decommissioning, Andra applied for an environmental permit in order to increase its disposal capacity for very low level waste at its Industrial Facility for Grouping, Sorting and Disposal (CIRES) facility. Enresa (Spain), announced a significant increase of up to four times the lowlevel waste disposal capacity at the El Cabril disposal facility. Switzerland’s National Cooperative for the Disposal of Radioactive Waste (Nagra) is awaiting permission to conduct underground investigations at its recommended site. Other Member States, such as Germany, Japan, Ukraine and the United Kingdom, are actively engaged in siting processes.

Innovations in radioactive waste management saw the companies Studsvik (Sweden) and Gesellschaft für Nuklear-Service (Germany) sign an exclusive agreement to implement Studsvik’s ‘inDRUM’ technology, a patented technology for treating challenging radioactive waste. In the Russian Federation, the Tomsk Polytechnic University and TVEL are collaborating on a project that uses electric discharges to expedite the decontamination of radioactive concrete. This innovative method promises faster and more efficient decontamination

FIG. C.4. During his official visit to France in 2023, Director General Rafael Mariano Grossi visited ANDRA's installation in Meuse/Haute-Marne, including a presentation by ANDRA's Director General Pierre-Marie Abadie of Cigéo's project for radioactive waste deep geological disposal. (Source: ANDRA)

while minimizing dust dispersion, which is often associated with traditional concrete crushing methods. The Russian Federation's Institute of Physics and Power Engineering developed a technology for solid-phase oxidation of sodium coolant of fast reactors and created a pilot industrial facility MINERAL 100/150. The Decommissioning Alliance (United Kingdom), a partnership comprising the companies Jacobs, Atkins and Westinghouse Electric Company, is pioneering an innovative approach to safely retrieve debris from fuel ponds at a Nuclear Decommissioning Authority (NDA) site. The Bulk Sludge Retrieval Tool has been tested, offering an efficient and cost-effective solution akin to an industrial vacuum cleaner.

FIG. C.5. Director General Rafael Mariano Grossi receives a guided tour of the Swedish Nuclear Fuel and Waste Management Company's Canister Laboratory, including a tour of canisters for the deep underground storage of spent fuel, during his official visit to Sweden in August 2023. (Source: IAEA)

During the reporting period, several Member States with more recent and/or smaller-scale responsibilities established national capacity and facilities. For example, Belarus is making significant progress in establishing an organization for radioactive waste management. The State's goal is to have a long term storage and disposal facility operational by 2030, which would cover waste generated not only by the Belarusian NPP but also from various sectors that use ionizing radiation sources. The Netherlands has started construction on the Multifunctional Storage Building, a new facility for low and intermediate level radioactive waste, with a design lifespan of at least 100 years. Zimbabwe has completed the construction of a national centralized radioactive waste management facility for the longterm management of radioactive waste and disused sealed radioactive sources. The safety and security conditions of the national storage facilities in the Philippines and the Bolivarian Republic of Venezuela were improved, increasing the available storage capacity for the near future.

FIG. C.6. The newly constructed centralized waste management facility in Zimbabwe. (Source: IAEA)

FIG. C.7. Improved storage facility conditions in the Philippines (left) and the Bolivarian Republic of Venezuela (right). (Sources: Philippine Nuclear Research Institute (left) and Venezuelan Institute for Scientific Research (right))

In July 2023, Slovenia's Agency for Radwaste Management (ARAO) started site preparation for construction of its low and intermediate level waste disposal facility, establishing primary access roads, necessary utility connections and baseline environmental monitoring. In Australia, however, after a Traditional Owner representative body successfully challenged the selection of the preferred site for a centralized radioactive waste management facility in South Australia on the grounds of apprehended bias, the Government does not intend to proceed with the preferred site.

FIG. C.8. Site preparation for the construction of an NPP operational waste disposal facility in Slovenia. (Source: ARAO)

Trends

The global trend towards adopting integrated radioactive waste management principles and practices is transforming the nuclear industry. This approach ensures the sustainable utilization of nuclear technology by optimizing waste handling, from waste generation to disposal. It requires coordination between policy and strategy developers to address various challenges related to the adequacy of set goals and to then select adequate technical options on integrating radioactive waste management. Integrated waste management streamlines processes, mitigates environmental risks and fosters responsible radioactive waste management. The Nuclear Waste Management Organization in Canada has adopted an integrated strategy for managing radioactive waste, excluding used nuclear fuel. This comprehensive approach includes the disposal of intermediate level waste and non-fuel high level waste in a deep geological repository and low level waste in near surface disposal facilities.

Member States' interest in deploying SMRs is set to transform the field of nuclear energy. However, SMRs bring a significant challenge to radioactive waste management. As countries embrace this innovative technology, suitable policies and strategies for radioactive waste must adapt to accommodate SMRs. This necessitates substantial investment in waste processing, storage, and disposal facilities, as well as the training of qualified personnel. Funding provisions, particularly for disposal facilities, are crucial to addressing these evolving radioactive waste management responsibilities, ensuring a sustainable future for nuclear energy.

Another growing trend is the adoption of the radioactive waste hierarchy, focusing on waste prevention, minimization, recycling and reuse. This approach aims to curtail the volume of radioactive waste destined for disposal facilities, leading to the preservation of these facilities as valuable long term assets. One manifestation of this trend is Ontario Power Generation's Western Clean-Energy Sorting and Recycling facility, which minimizes waste from NPPs, reducing storage needs and decommissioning costs. In addition, Belgium's RECUMO facility for recycling radioactive residues from medical radioisotope production and recovering low enriched uranium (LEU) further demonstrates a commitment to waste reduction. Similarly, Korea Hydro & Nuclear Power Company's tritium removal facility in Romania showcases the drive to limit waste generation while fostering expertise in tritium management. In the United Kingdom, Nuclear Waste Services published its radioactive waste management strategy, expressing alignment with the waste hierarchy principles. This strategy emphasizes waste reduction, setting a 50% recycling target for decommissioning waste and aiming to reduce secondary waste by approximately 70% by 2030.

Nuclear scientists are contemplating how value can be extracted from waste to recover radioisotopes for medical applications and space exploration. The UK Space Agency and the UK National Nuclear Laboratory are investigating americium-241 space batteries. In 2023, a total of 32 high activity sources were removed from Chile and Slovenia. In addition, under the Global Radium-226 Management Initiative, disused radium sources were removed from Thailand. Engagements are currently ongoing in 17 Member States including Croatia, El Salvador, Ethiopia, Indonesia, Malaysia, Slovenia and Spain, in order to take stock of available disused radium sources for radioisotope production for cancer treatment.

■ D.
Fusion Research and Technology Development for Future Energy Production

D. Fusion Research and Technology Development for Future Energy Production

Status

In 2023, researchers at the US Lawrence Livermore National Laboratory repeated at least three times the fusion energy ignition breakthrough achieved at the National Ignition Facility in December 2022.

FIG. D.1. Director General Rafael Mariano Grossi, visiting the SPARC tokamak hall. (Source: IAEA)

In February 2023, Commonwealth Fusion Systems (CFS) and the Massachusetts Institute of Technology's (MIT's) Plasma Science and Fusion Center (PSFC), the first Agency Collaborating Centre in the field of fusion energy, celebrated the official opening of the construction site for SPARC — a tokamak planned to generate a net scientific energy gain. SPARC is expected to become operational in 2025 and demonstrate net scientific energy gain thereafter. Its successor, ARC, is expected to be completed by 2035 and demonstrate electricity production.

In October 2023, Japan's JT-60SA tokamak produced its first plasma. The four-storey tall machine is designed to hold plasma heated to 200 million degrees Celsius for about 100 seconds, far longer than previous large tokamaks. Plasmas in JT-60SA will closely resemble those planned for ITER and should allow physicists to study plasma stability and how it affects fusion power output at long timescales, providing lessons that can be applied to the larger tokamak. Also in Japan, the Linear IFMIF Prototype Accelerator has been installed in Rokkasho, Japan in 2023.

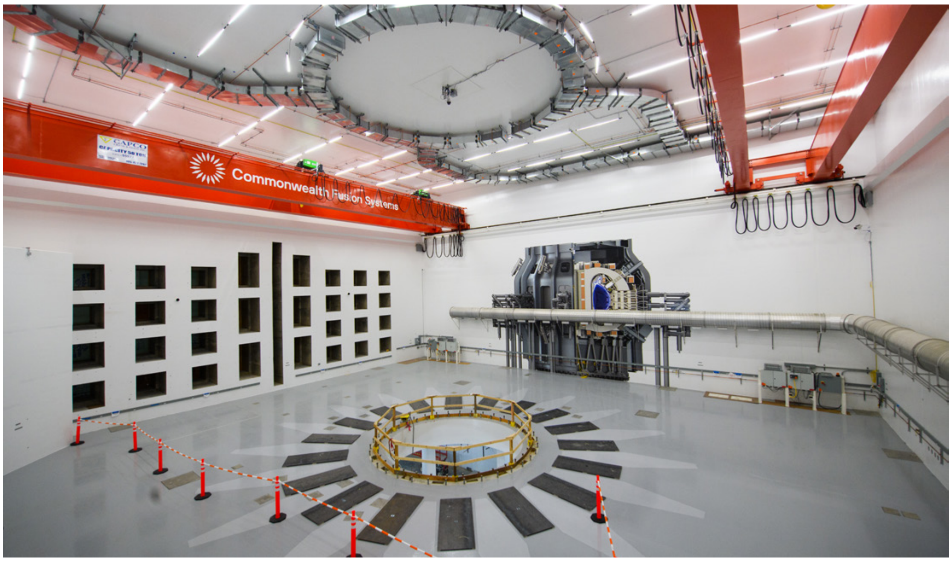


FIG. D.2. The SPARC tokamak hall ready for machine assembly. (Source: CFS)

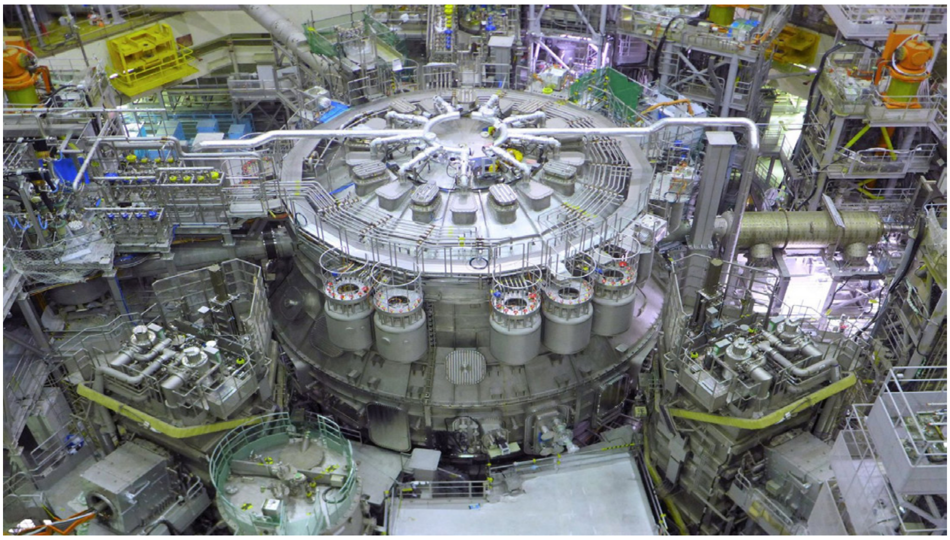


FIG. D.3. JT-60SA is the largest tokamak in operation, designed and built jointly by Japan and the European Union. (Source: National Institutes for Quantum Science and Technology)

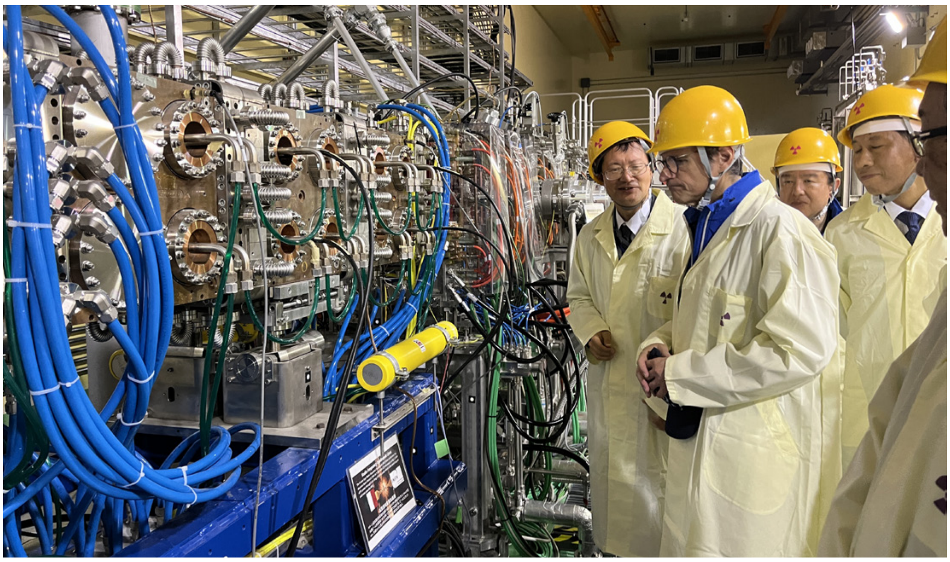


Fig. D.4. Rafael Mariano Grossi, IAEA Director-General, visits the Linear IFMIF Prototype Accelerator at the Rokkasho Fusion Institute during his official visit to Japan. (Source: National Institutes for Quantum Science and Technology)

The Experimental Advanced Superconducting Tokamak (EAST) in China achieved a steady state high confinement long plasma operation for 403 seconds. This breakthrough improved on the original record of 101 seconds, which was set by EAST in 2017. The temperature and density of particles were greatly increased during the high confinement plasma operation, which will improve the power generation efficiency of future fusion power plants. Also in China, the HL-3 tokamak operated for the first time in high confinement mode with a plasma current of one million amperes, owing to upgraded heating, operation, control, diagnostic and power supply systems.

In 2023, France's WEST tokamak started operating its tungsten divertor. A first experimental campaign producing high neutron fluence through a succession of plasma pulses of about one minute was conducted to demonstrate the resistance and performance of this new component.

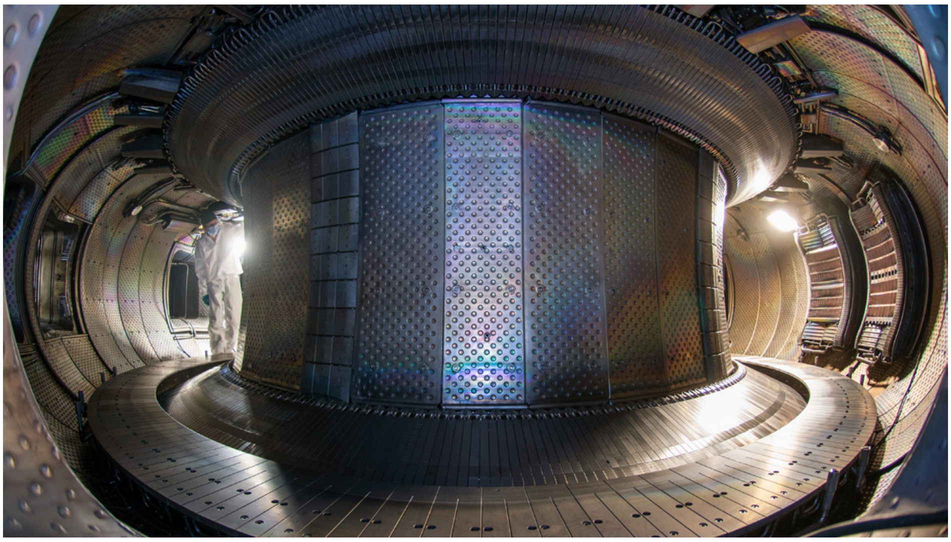


FIG. D.5. WEST tokamak equipped with its actively cooled tungsten diverter. (Source: CEA)

Following 40 years of operation and the final deuterium–tritium experiments conducted throughout 2023, the decommissioning of the Joint European Torus (JET) has begun and will continue until around 2040. JET's decommissioning will provide valuable information for the fusion community by enabling analysis of how the in-vessel materials changed over time of operation.

Researchers at the Wendelstein 7-X in Germany, the world's largest stellarator, were able to achieve an energy turnover of 1.3 gigajoules (GJ). In future, Wendelstein 7-X aims to reach an energy turnover of 18 GJ, with the plasma being kept stable for half an hour.

In 2023, the ITER Organization and its Domestic Agencies continued to advance toward the development of an optimized baseline for ITER that would involve a change of first wall material from beryllium to tungsten, which is expected to enhance the resilience of in-vessel components while minimizing the amount of tritium retained within the machine. Progress was achieved on repairs of key components as well as ongoing manufacturing, assembly and installation, while the ITER Organization also continued to engage with France's Nuclear Safety Authority on the incorporation of a phased approach to licensing that encompasses three experimental operational stages, each catering to specific milestones and safety requirements for steering the ITER project towards successful completion. Council Members emphasized the strong value of ITER and its mission.

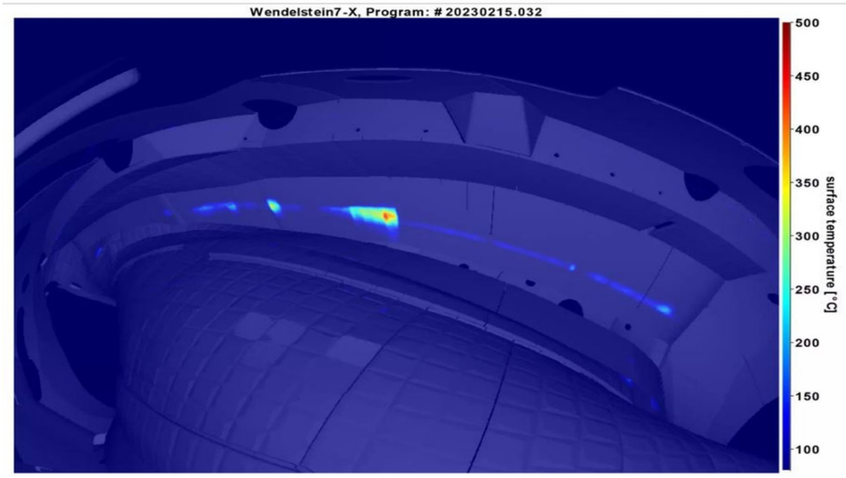


FIG. D.6. An infrared image from the vacuum vessel of Wendelstein 7-X, showing the temperature distribution at the water cooled divertor baffles. A defined line in the centre, the so-called strike line, is clearly visible. This is where the plasma touches the divertor and the temperature is highest. In individual areas, temperatures of up to 600 degrees Celsius are reached (red areas). The divertor tiles can withstand temperatures of up to 1200 degrees Celsius. (Source: Max Planck Institute for Plasma Physics)

In Italy, progress continued in the construction of the Divertor Tokamak Test (DTT) facility, a new superconducting tokamak devoted to the study of advanced divertor solutions for demonstration fusion power plants (DEMO). Composed of many Italian research institutions and international partners, including one of the biggest energy companies in the world, the consortium implementing the project has raised nearly €500 million to construct the facility. The DTT's primary mission is to explore and test the physics and technology of concepts for plasma power exhaust that could be used in the European DEMO plant.

The objective of DEMO plants is to demonstrate net electrical gain from fusion energy. At least 12 such concepts are at various stages of development in China, the European Union, Japan, the Republic of Korea, the Russian Federation, the United Kingdom and the United States of America, with target completion dates ranging between 2030 and 2050. These concepts are being developed by individual governments, private companies and some public–private joint ventures (FIG. D.4).

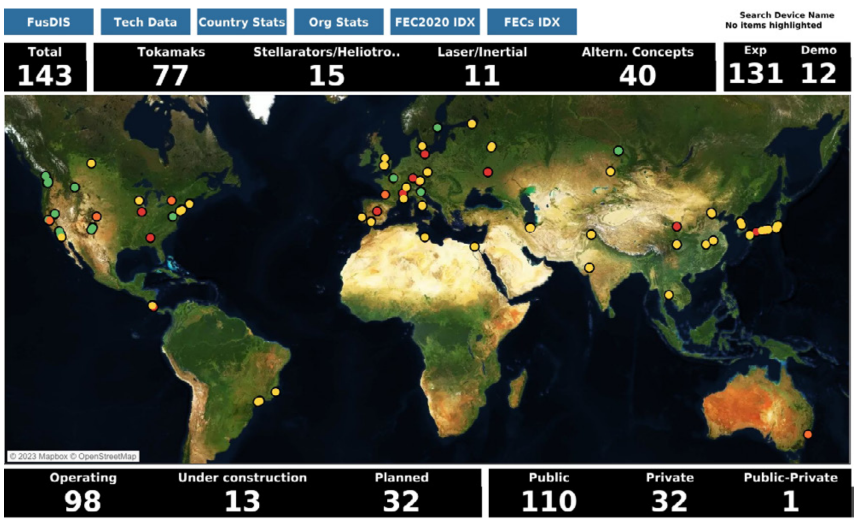
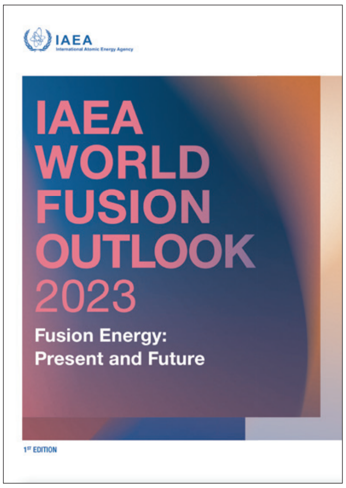


FIG. D.7. Over 140 experimental, public and private fusion devices are in operation, under construction or being planned, while a number of organizations are considering designs for demonstration fusion power plants. (Source: IAEA Fusion Device Information System)

Trends



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At the 29th IAEA Fusion Energy Conference, organized by the Agency and the UK Government in London in October 2023, the Director General introduced the first IAEA World Fusion Outlook, a global reference for authoritative information on the latest developments in fusion energy, and also announced the inaugural meeting of the World Fusion Energy Group, which will convene in 2024. During the conference, the United Kingdom announced the Fusion Futures Programme, which would see an additional £650 million (US $793 million) invested over the next five years in a package of R&D programmes, including the creation of 2200 training places, a new fuel cycle testing facility and funding to develop infrastructure for private fusion energy companies, notably at the United Kingdom Atomic Energy Authority's (UKAEA's) Culham campus. This announcement followed the country's decision to leave the Euratom Research and Training Programme. A few weeks later, the UK Department for Energy Security and Net Zero and the US Department of Energy announced a new strategic partnership to accelerate the demonstration and commercialization of fusion energy, focused on advancing their national fusion energy strategies.

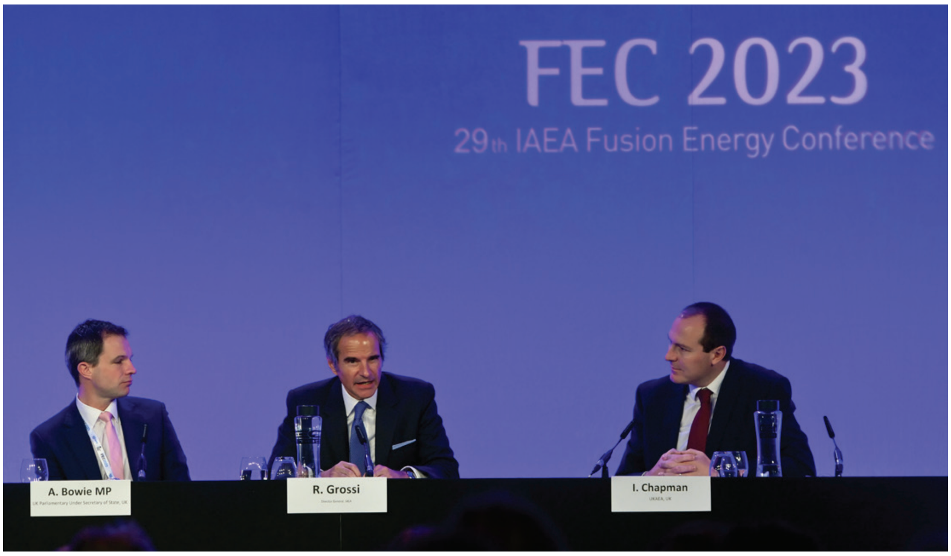


FIG. D.8. The opening ceremony of the 29th IAEA Fusion Energy Conference in London. From left: Andrew Bowie, Parliamentary Under Secretary of State (Minister for Nuclear and Networks) at the Department for Energy Security and Net Zero; Rafael Mariano Grossi, IAEA Director General; and Ian Chapman, Chief Executive Officer of the UKAEA. (Source: IAEA)

Meanwhile, in Germany, the Federal Ministry of Education and Research announced that it would provide more than €1 billion for fusion research by 2028, in addition to the €370 million (US $396 million) already earmarked for research institutions over the next five years.

Japan adopted its first national strategy on fusion energy, highlighting the need to create a domestic industry in fusion energy involving wider participation of the private sector in fusion energy R&D. The Japanese Government also announced that it would establish a fusion energy industry council to develop the related industries, as well as draw up guidelines for fusion energy technology regulation. In addition, the Government will prioritize fusion energy education in academia.

The US Department of Energy (DOE) Office of Fusion Energy Sciences released its "Building Bridges" vision outlining three key elements: 1) workforce development and sustainment — ensuring the establishment of sustainable and resilient pathways for diverse and exceptional talent; 2) bridging gaps — creating innovation engines with national laboratories, universities, and industry to resolve R&D gaps and support domestic supply chains for fusion energy; and 3) transformational science — nurturing plasma science and technology discovery translating to innovation impact. The vision is part of an overall fusion strategy that aims to help converge private and public sector activities in fusion R&D.

Private sector companies are receiving growing attention and investments in the field of fusion energy, as many aim to independently develop their own research and demonstration devices. US private company Helion announced an agreement with Microsoft to provide the latter with electricity from its first fusion power plant, which is expected to be online by 2028, with a target power generation of 50 MW. Helion also announced a collaboration with the company Nucor to develop a 500 MW fusion plant to power a Nucor steelmaking facility, with a target operations start date of 2030.

In the changing landscape of fusion energy, public–private partnerships are beginning to form. In May 2023, the US Department of Energy announced US $46 million in funding for 8 companies for their first 18 months of advancing designs and R&D for fusion power plants, as part of its Milestone-Based Fusion Development Program. The chosen companies were among many that submitted proposals detailing their plans to bring commercial fusion energy to market and will receive reimbursement funding only after pre-established commercialization milestones are achieved and verified by the US Department of Energy. In the framework of the 'France 2030' call for projects, one company was awarded the development of a stellarator fusion reactor.

The fusion energy industry overall is seeing year-on-year increases in funding. The annual fusion industry report released by the Fusion Industry Association, entitled The global fusion industry in 2023, which is the third such report, shows that the fusion energy industry has now attracted a total of US $6.21 billion in investment (up from US $4.8 billion in 2022). The report surveyed 43 private fusion energy companies, ranging from established companies to new entrants. Although the United States of America continues to lead the field, with 25 active fusion energy companies (including many of the largest), the industry is becoming more geographically diverse, with at least 1 fusion energy company in 12 countries.

Regulatory bodies and lawmakers are also beginning to address the challenges and opportunities of fusion energy. In 2023, California was the first state in the United States of America to recognize fusion energy as a separate and distinct technology from fission energy. The legislation highlighted the safety and environmental advantages of fusion energy and laid the foundation for future state regulations. This followed the unanimous vote of the NRC to separate fusion energy regulation from fission energy and regulate near-term fusion energy systems under the by-product material framework (such as, for example, particle accelerators).

The UK Government confirmed that all planned fusion prototype energy facilities in the United Kingdom would continue to be regulated by the Environment Agency and the Health and Safety Executive, unlike NPPs, which are regulated by the Office for Nuclear Regulation.

In addition, the Agile Nations working group on fusion energy, comprised of Canada, Japan, and the United Kingdom, as members, with Bahrain and

Singapore as observers, produced joint recommendations that recognize the important contribution that fusion energy could make to the global challenges of climate change and energy security, as well as the benefits of a harmonized approach to fusion energy regulation being adopted by several countries; and that advocate clarity on a regulatory framework that would apply to fusion energy facilities independent of the fusion technology and that maintains appropriate protections for people and the environment, proportionate to the hazards of fusion energy, while remaining transparent and pro-innovation.

Supercomputing, AI and the 'Industrial Metaverse' also saw a rise in interest. In 2023, a collaboration between the UKAEA, Dell Technologies, Intel and the University of Cambridge was announced. This collaboration aims to explore how supercomputers and AI technologies with advanced predictive capabilities can deliver a digital twin of the Spherical Tokamak for Energy Production (STEP) — the United Kingdom's prototype fusion power plant design. In addition, the US Department of Energy announced US $29 million in funding for seven team awards for research in machine learning, AI and data resources for fusion energy sciences. MIT's PSFC was one of the seven recipients, receiving US $5 million in funding for a project endorsed by the Agency entitled "Open and FAIR Fusion for Machine Learning Applications". The project aligns with the IAEA—PSFC Collaborating Centre agreement and with the Agency's coordinated research project entitled "Artificial Intelligence for Accelerating Fusion Research and Development", for which the PSFC is the technical coordinator.

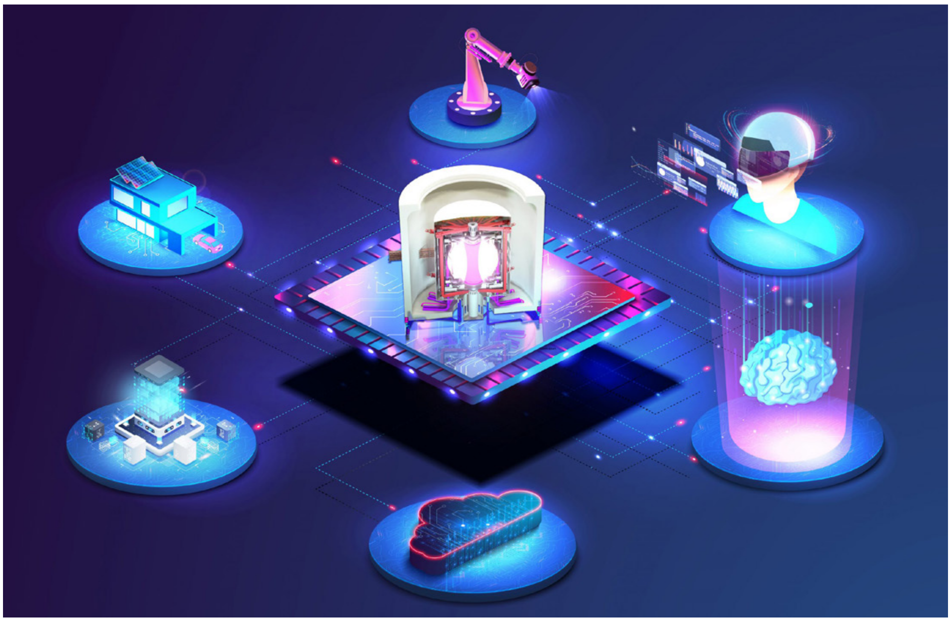


FIG. D.9. Supercomputing, AI and the 'Industrial Metaverse' will advance the development of STEP — the United Kingdom's prototype fusion power plant. (Source: UKAEA)

E.

Research Reactors, Particle Accelerators and Nuclear Instrumentation

E. Research Reactors, Particle Accelerators and Nuclear Instrumentation

E.1. Research Reactors

Status

There were 234 operational research reactors, including those in temporary shutdown, in 54 countries at the end of 2023. These research reactors continued to generate neutron beams; to provide indispensable irradiation services for science, medicine and industry; and to enhance education and training programmes. The most frequent applications of research reactors are shown in Table E-1 in the Annex.

Less than 10% of the world's research reactor fleet is currently responsible for supplying most of the world market with important medical radioisotopes, such as technetium-99m, iodine-131, lutetium-177 or holmium-166, and for testing nuclear fuels and structural materials for future advanced power reactors has led to several projects to establish new high power and multipurpose research reactors. Some examples are the RA-10 research reactor nearing completion in Argentina and the continuing construction of the Ki-Jang Research Reactor in the Republic of Korea, the Jules Horowitz Reactor in France, for which the continued investment to finalize the construction was approved, and the Multipurpose Fast Research Reactor in the Russian Federation; the announcement of the full financing and the start of preparatory construction work for the PALLAS reactor in the Netherlands; the renewed governmental commitment to the Brazilian Multipurpose Reactor in Brazil; and recent governmental endorsement of a replacement for the 58-year-old SAFARI-1 reactor in South Africa.

Overall, 11 new research reactors, including 1 accelerator driven system, are under construction in 10 countries: Argentina, the Plurinational State of Bolivia, Brazil, China, France, the Islamic Republic of Iran, the Republic of Korea, the Russian Federation, Saudi Arabia and Ukraine. In 2023, a new subcritical nuclear facility, VR-2, started operation in the Czech Republic.

At the end of 2023, 14 Member States had formal plans to construct new research reactors, namely Bangladesh, Belarus, Belgium, China, India, the Netherlands, Nigeria, the Philippines, South Africa, Tajikistan, Thailand, the United States of America, Viet Nam and Zambia. In addition, a significant number of countries are considering building research reactors, namely Azerbaijan, Ethiopia, India, Iraq, Kenya, Malaysia, Mongolia, Myanmar, the Niger, the Philippines, Rwanda, Senegal, the Sudan, Tunisia, Uganda and the United Republic of Tanzania.

International efforts continued to minimize high enriched uranium (HEU) use in the civilian sector. With the complete conversion from HEU to LEU in molybdenum-99 production in Belgium, all major global producers of this highly

11 new research reactors, including

1 accelerator driven system,

are under construction in **10** countries

- Argentina
- Bolivia, the Plurinational State of
- Brazil
- China, the People's Republic of
- France
- Iran, the Islamic Republic of
- Korea, the Republic of
- Russian Federation
- Saudi Arabia
- Ukraine

FIG. E.1 a. The construction of the RA-10 research reactor is nearing completion in Argentina. (Source: Argentina's National Atomic Energy Commission)

FIG. E.1 b. The VR-2 subcritical nuclear facility started operation in 2023 in Czech Republic. (Source: Czech Technical University) in-demand medical radioisotope have used non-HEU production methods since April 2023. In total, to date, 109 research reactors and major medical isotope production facilities have been converted from the use of HEU to LEU or were confirmed as being shut down and 6925 kilograms of HEU have been repatriated to their country of origin or otherwise dispositioned from 48 countries (and Taiwan, China).

Trends

Member States are increasing utilization of their operational research reactors to support the energy transition and decarbonization under SDG 7 (affordable and clean energy). Neutron techniques, such as neutron imaging and neutron depth profiling, are used to characterize hydrogen fuel cells and lithium-ion batteries. A number of research reactors are used for irradiation and testing of structural materials and fuels, activities that are essential for the development of both nuclear fission and fusion new energy concepts and to support the renewed interest in nuclear research, development and demonstration that has emerged in several countries, including the United States of America. The Neutron Radiography Reactor (NRAD) of the Idaho National Laboratory (INL) has unique experimental capabilities to routinely analyse highly radioactive samples, enabling staff to conduct research on irradiated nuclear fuels and structural materials, aiding the development of innovative nuclear energy solutions. The INL revised their strategy in 2023, in order to actively pursue expanded utilization of NRAD to aid the development of innovative nuclear energy solutions.

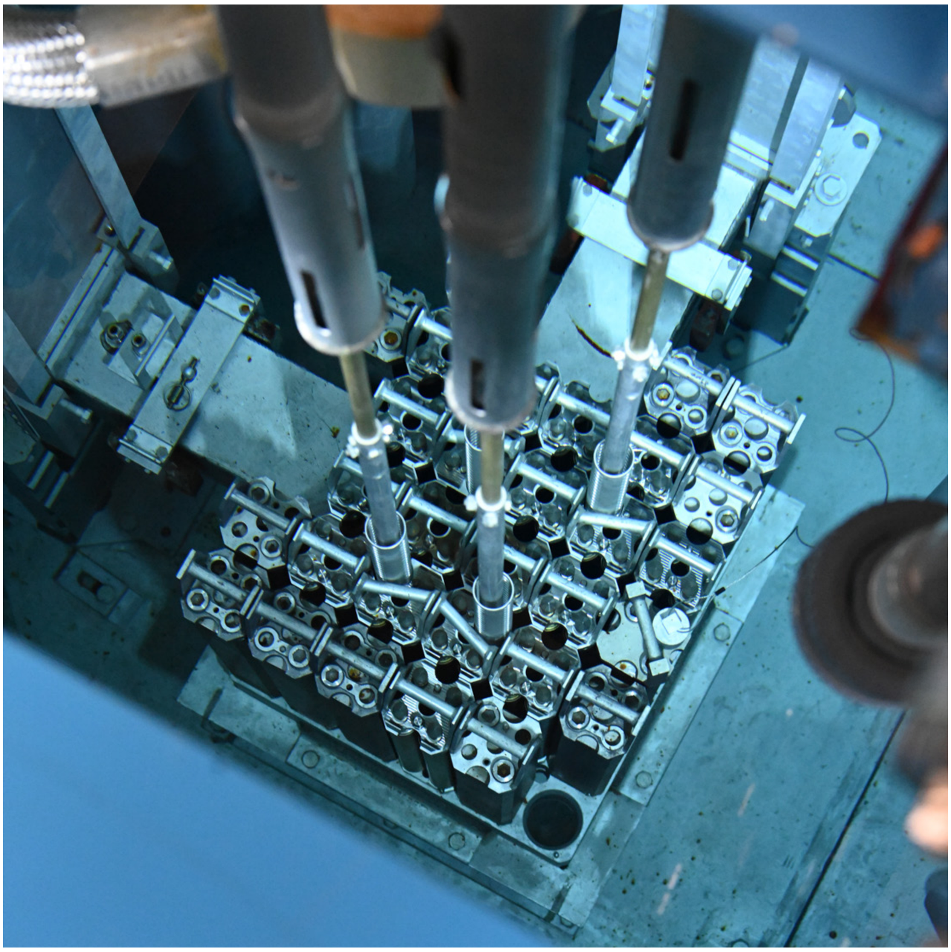


FIG. E.2. A view of NRAD's reactor core with its internal equipment for materials research at the INL. (Source: INL)

MIT's research reactor is also expanding its capabilities to enlarge its activities in the field of materials irradiation relevant to nuclear fission and fusion, complementing the work of the INL and other US nuclear research facilities. The Agency supported both institutions in their expansion projects through Integrated Research Reactor Utilization Review missions conducted in mid-2023.

Testing of advanced reactor technologies remains one of the important applications of research reactors. The Russian Federation is preparing to build the country's first 10 MW molten salt research reactor to demonstrate the practical feasibility of molten salt fuel technology and burning minor actinides. A construction licence is expected in 2027.

The progressive ageing of the research reactor fleet worldwide has pushed operators and regulators towards adopting new techniques and methodologies to assess research reactor operating conditions for continuous safe operation. One such methodology is Time Limited Ageing Analysis (TLAA), which is aimed at evaluating the operating conditions and the residual lifetime of systems, structures and components, particularly those that involve high costs to inspect and replace and have a significant impact on the reactor's operational availability. TLAA has been successfully applied in support of the LTO of NPPs. Several research reactor operators have already started using TLAA to support the extension of their operating licences. Owing to differences with power reactors, the application of TLAA for research reactors requires an appropriate graded approach. A joint effort is currently being considered to establish a common methodology, applicable to all Member States.

Many countries take advantage of opportunities to access research reactors through international and regional collaboration initiatives, such as the IAEA-designated International Centre based on Research Reactor scheme. There are currently seven such centres across four continents, with the latest one designated in Morocco, in 2023.

E.2. Particle Accelerators

Status

For everything from motors and medicines to plastics and proteins, detailed scientific studies are dependent on how many neutrons can be produced and made available for researchers by a neutron source. Therefore, in addition to research reactors, scientists and engineers continued to develop a new generation of neutron sources based on particle accelerators and spallation target technology. In 2023, the construction phase of the European Spallation Source (ESS), one of the world's largest science and technology infrastructure projects, progressed steadily. In addition, considerable advancement in the commissioning of the most powerful linear proton accelerator ever built, a helium cooled tungsten target wheel, as well as its associated state-of-the-art neutron instruments, was achieved at the facility, through collaboration between Member States and many in-kind contributions. Some of the major milestones recently achieved at the ESS include the completion of proton accelerator commissioning and the installation of the permanent shielding for the target monolith vessel as well as the moderator and the neutron production rotating target wheel. In parallel, significant progress was achieved in the installation of the sophisticated experimental set-ups for the 15 selected cutting-edge neutron beamlines and scattering instruments (also called neutron beam end stations).[5]

[5] ESS Instruments web page: https://europeanspallationsource.se/instruments

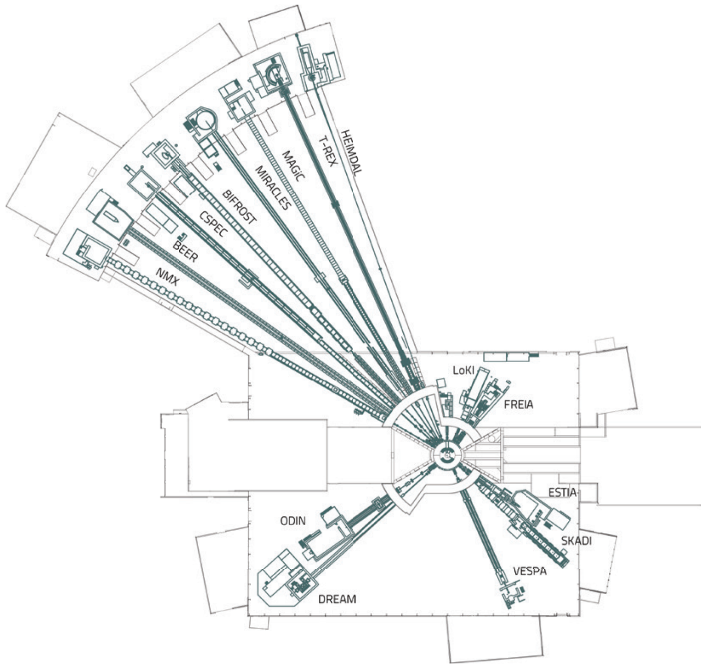


FIG. E.3. A set of neutron scattering and spectroscopy instruments to be offered by the future generation accelerator-based neutron source at ESS. (Source: ESS)

In early 2023, during the first meeting of the International Fusion Materials Irradiation Facility — Demo Oriented Neutron (IFMIF-DONES) Steering Committee,[6] the highest governing body of the IFMIF-DONES Programme, the start of the construction phase of IFMIF-DONES in Escúzar, Granada, Spain, was officially announced. This is a significant milestone in the development of the international fusion programme, which is based on three main pillars: ITER, DEMO and IFMIF-DONES[7]. The facility, consisting of a state-of-the-art accelerator, liquid lithium target and irradiation tests module, will provide DEMO with the necessary experimental data for materials irradiation and testing capabilities under comparable irradiating conditions. In parallel with progress in the construction of the infrastructure, activities were carried out to promote and boost collaboration in research, development and innovation projects in the field of fusion and other related fields of science and technology, such as radioisotope production and nuclear data measurements.

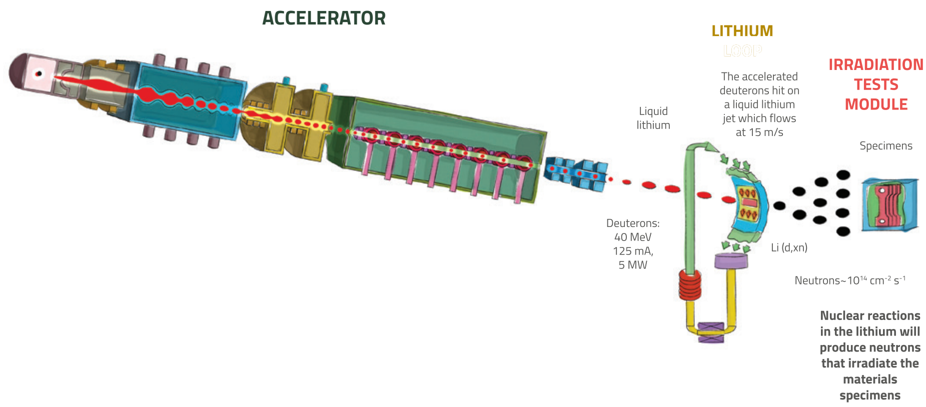


FIG. E.4. Schematics of the IFMIF-DONES facility based on a high-power deuteron accelerator, liquid lithium target loop for high energy neutron production and a material irradiation tests module. (Source: IFMIF-DONES)

[6] https://fusion.bsc.es/index.php/2023/04/13/ifmif-dones-starts-construction-phase/
[7] IFMIF-DONES home page: https://ifmif-dones.es/

Trends

Particle accelerators have a key role in sub-cellular imaging and irradiation for cancer treatment. For the purpose of medical diagnostics, a wide range of imaging techniques such as ultrasound, computed tomography and magnetic resonance imaging are regularly used. As ion and X-ray beam manipulation techniques become increasingly sophisticated, it is possible to focus the ion or X-ray beams down to nanometre scale. By scanning such a tiny beam over an artefact in combination with various detector systems, in addition to the analytical information gained, the artefact image becomes more and more important in itself. The identification of pigments, discovery of hidden sketches under a painting and even the revealing of the internal structure of antique scrolls have become possible with the emergence of novel multispectral imaging methods. Furthermore, similarly as in medical imaging for diagnostics purposes, sophisticated, machine learning based image processing methods are being developed to improve the visualization of an artefact, or even its missing details.

The recent trend in heritage imaging is to apply multimodal imaging combined with image processing. There are some additional commonalities with medical imaging as, for example, both patients and artefacts are fragile and the radiation dose delivered, either for irradiation or for analysis, is critical in order to minimize possible radiation damage for the maximum radiation therapy effect or for collecting indispensable analytical information. Therefore, medical applications are a strong motivator for accelerator science and technology research in relation to accurate and controllable delivery of the particle/X-ray dose.[8] Such demands in the medical field, along with multispectral imaging, are transforming the capabilities of heritage imaging as well.[9]

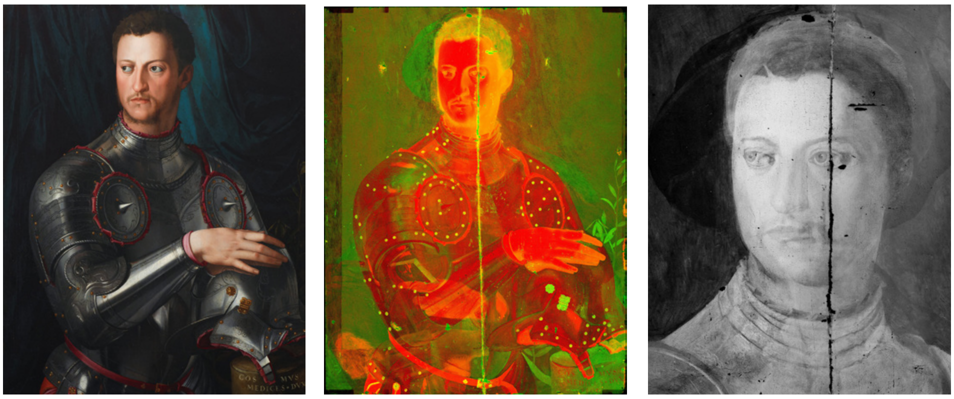


FIG. E.5. Australian synchrotron high-definition X-ray fluorescence microscopy based image of a 16th-century Bronzino painting of Duke Cosimo de' Medici (left) has revealed an underlying portrait as well as allowed detecting and mapping metals in paint pigments non-invasively (right). The lead (Pb) elemental distribution map is showing the original painting clearly e.g. around the head and shoulder (and indicates also the eye of another person underneath). (Source: Art Gallery of New South Wales (left), Australian Nuclear Science and Technology Organisation (centre and right))

[8] Bertrand, L. et al. Practical advances towards safer analysis of heritage samples and objects. TrAC Trends in Analytical Chemistry, Volume 164 (2023). https://doi.org/10.1016/j.trac.2023.117078

[9] Gibson, AP. Medical imaging applied to heritage. The British Journal of Radiology 96, No 1152 (2023). https://doi.org/10.1259/bjr.20230611

E.3. Nuclear Instrumentation

Status

The deployment of uncrewed ground vehicles (UGVs), in addition to conventional instrumented backpacks and drones, offers a multitude of advantages in the field of radiation mapping. These terrestrial platforms come in a diverse range of forms, with wheeled, legged, and tracked robots representing the most prevalent types. UGVs can be purpose-designed to withstand high dose rates, allowing them to perform tasks such as the dismantling and decommissioning of nuclear facilities. The robots can operate in one of two modes: remotely controlled (teleoperated) or autonomously, leveraging well-suited sensors and sophisticated algorithms. In certain outdoor environments, satellite navigation comes into play, although the prevailing trend is the adoption of light detection and ranging (LIDAR) based simultaneous localization and mapping, which is also applicable indoors. Presently, it is feasible to employ off the shelf localization stacks to ensure autonomous navigation. The sensor array common to this field includes LIDAR, radars, RGB systems and depth cameras and thermal imagers, as well as a variety of dose rate meters, spectrometers and other radiation detection systems. A contemporary trend is scene-data fusion, a technique that combines multiple data sources to enrich radiation measurements with contextual information. Data processing can be executed in real time, either through on-board computers or remote stations, necessitating the streaming of relevant data to local ground control stations or the cloud. Alternatively, data loggers can capture information for post-processing.

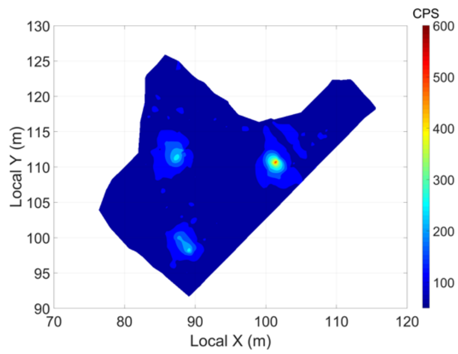


FIG. E.6. An instrumented UGV used in a training workshop at the Nuclear Science and Instrumentation Laboratory in Seibersdorf, Austria (left) together with the obtained radiation map of 'hot zones' (right). CPS stands for counts per second. (Source: IAEA)

Trends

Field programmable gate arrays (FPGAs) are increasingly used as an integral part of radiation detector data acquisition (DAQ) systems. They serve a wide range of purposes, from setting DAQ parameters and streaming/routing data, to performing advanced signal discrimination or even complete event reconstruction. Deployed data treatment algorithms are at the core of more complex functionalities, whether that be conventional or AI based. One such example is the implementation of gamma-neutron discrimination algorithms for FPGA embedded system applications. Mixed radiation fields are commonplace in many practical applications of ionizing radiation, where detectors with discriminatory power are a necessary tool. As an example, instead of applying the traditional approach of pulse shape discrimination in the time domain, it is possible to apply algorithms that can operate in the frequency domain. By carefully defining an appropriate figure of merit, it is possible to accelerate the analysis needed for the pulse shape (and radiation field) discrimination (see Figure E.7). This has led to real-time applications of such algorithms and its implementation has been the trend in modern DAQ systems in recent years, with a broad field of applications ranging from nuclear science and nuclear security to radiation protection and medical physics. Moreover, the spread of high-level synthesis, i.e., the possibility of coding the FPGA board in a high-level language, has made FPGAs accessible to more developers.

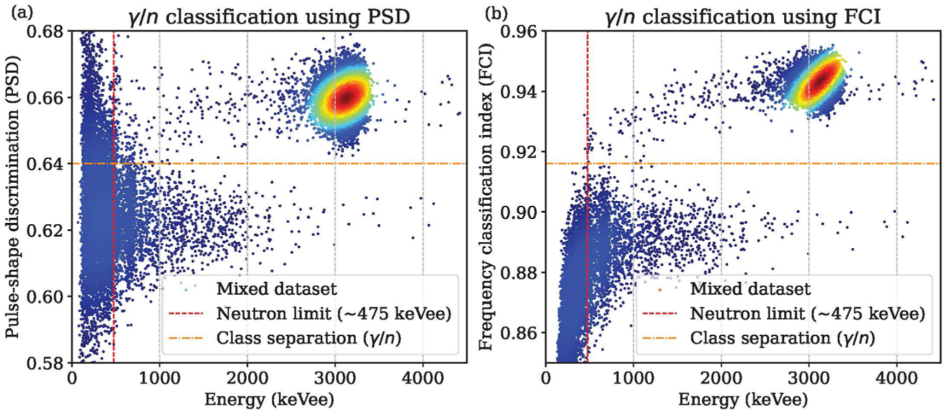


FIG. E.7. Comparison of γ/n separation with traditional pulse shape discrimination (left) and with a frequency classification index (right), where the latter qualitatively shows superior discrimination performance over the entire energy range. Experimental data was obtained at the Agency's Neutron Science Facility in Seibersdorf, Austria. (Source: Morales, I. R. et al., Gamma/neutron classification with SiPM CLYC detectors using frequency-domain analysis for embedded real-time applications)[10]

[10] Morales, I. R. et al. Gamma/neutron classification with SiPM CLYC detectors using frequency-domain analysis for embedded real-time applications. Nuclear Engineering and Technology (2023). https://doi.org/10.1016/j.net.2023.11.013

F.
Atomic and Nuclear Data

F. Atomic and Nuclear Data

Status

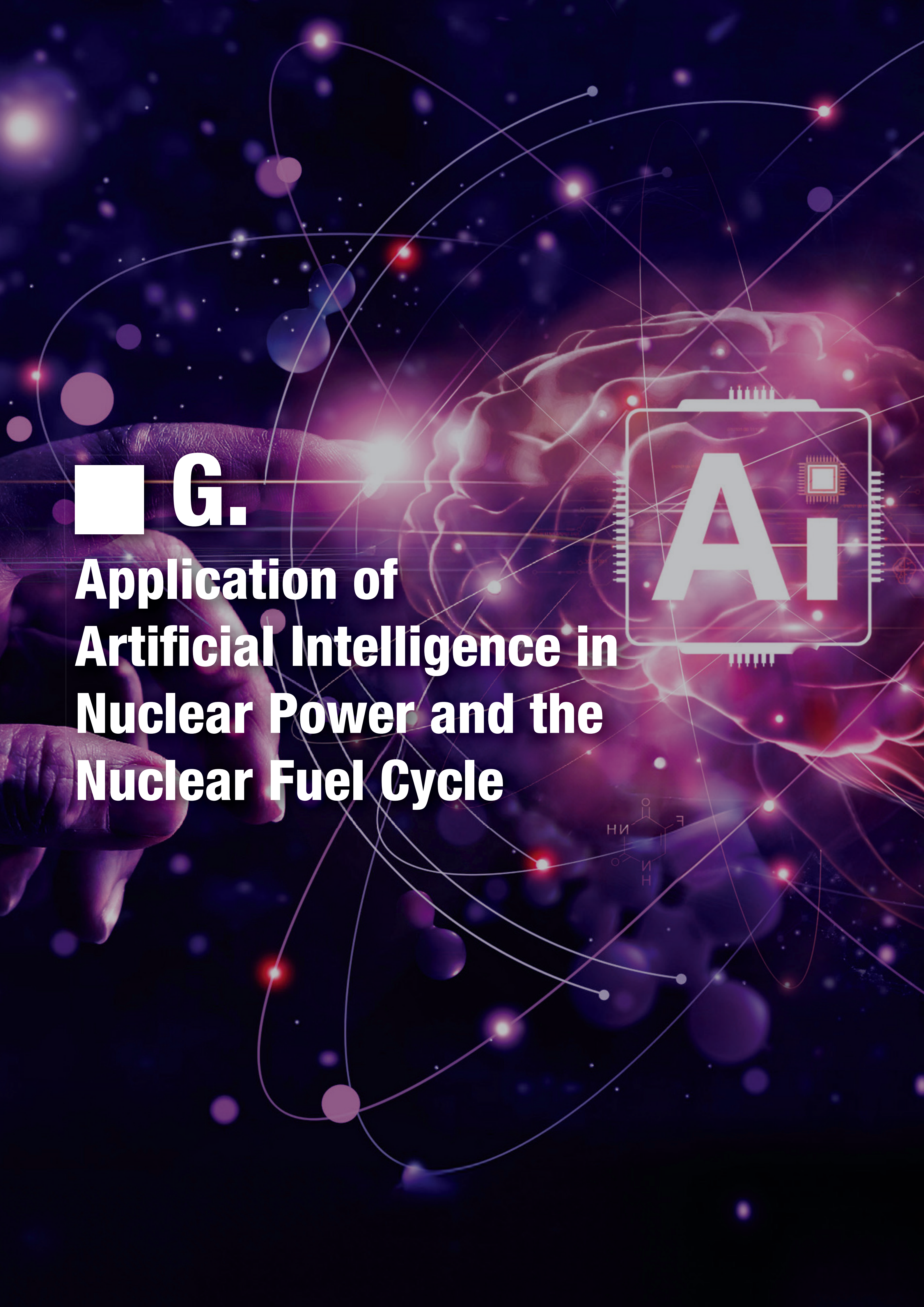
The development of ITER necessitates an increased reliance on nuclear and atomic numerical databases, as the nuclear simulation codes are becoming more advanced. For neutronics and material activation, this reliance concerns the use of the Fusion Evaluated Nuclear Data Library, while for atomic interactions in the fusion plasma, ITER makes use of the CollisionDB database.

Trends

Various Member States are investing more time and resources into ITER to obtain high-quality gamma interaction data. The main applications of such data are for active neutron interrogation, more precise estimates for gamma heating in the shielding of fission reactors and fusion devices and innovations in space applications. In order to achieve high-quality gamma interaction data, old nuclear databases involving gamma reaction data need to be updated with more recent experimental and theoretical information. New nuclear data evaluation efforts are under way to accomplish this.

The rapidly increasing global demand for medical radioisotopes, for both diagnosis and therapy, is also having a significant impact on nuclear data. Production cross sections with a much higher accuracy are required, in particular for optimized isotope production routes with a minimum level of impurities. This need for more accurate production cross sections requires further effort from experimental nuclear physicists and theoretical nuclear reaction modelers.

G. Application of Artificial Intelligence in Nuclear Power and the Nuclear Fuel Cycle



G. Application of Artificial Intelligence in Nuclear Power and the Nuclear Fuel Cycle

Status

Artificial intelligence (AI) is an umbrella term, encompassing various technologies developed over decades. AI holds promising potential for advancing nuclear energy production. Sophisticated AI systems mimic human logic in problem solving and decision making. With its capability to enhance efficiency, automation, safety and predictive maintenance, as well as to optimize processes, AI is already making strides in some areas of the nuclear field.

AI applications are being used at operating NPPs and fuel cycle facilities. These applications are currently independent of safety-related systems, processes or functions. In the case of non-destructive examination applications, for example, this ensures that the speed and accuracy of inspections is increased, decision makers regarding optimum core load designs are informed, and complex maintenance outage schedules are streamlined. Other AI applications include the improved assessment and optimization of advanced nuclear designs via AI assisted codes and mathematical models.

Current work concerning AI safety, security and reliability focuses on the identification of the risks and the consequences of the failures, ‘explainability’, trustworthiness and ethical considerations associated with continued AI deployment. AI future deployment scenarios involving facilities’ digital systems or processes may impact the nuclear safety or security of a nuclear power plant. Furthermore, as is typical for any digital system, appropriate measures ensuring validation and cybersecurity are being developed in parallel with various application scenarios. Concerned organizations are actively approaches to governing AI technology in nuclear and radiation facilities.

Trends

AI is increasingly being applied to commercial nuclear power and nuclear fuel cycle facility design and operation. It may improve safety, operational efficiency and cost-effectiveness while also facilitating the development of advanced nuclear technologies. AI-based systems help in analysing big data collected during operation to increase operational reliability and for preventing accidents with personnel. These advancements contribute to the sustainability and competitiveness of nuclear energy in the modern energy landscape.

AI is employed in various ways to enhance safety, efficiency and cost-effectiveness in the nuclear industry. With respect to safety and maintenance, AI is applied to predict equipment failures, analyse sensor data, and optimize maintenance schedules, to reduce downtime and improve safety. For example, certain machine learning algorithms currently can help detect anomalies and improve early warning systems. AI is also increasingly used to effectively identify low level correlations of events (including repeating ones) in historical unstructured data sources and documents. This approach makes it possible to identify systemically recurring events for which corrective measures were not taken, as well as to reduce the search time for significant events by an order of magnitude (investigation of violations, deviations, significant defects, etc.).

R&D in AI implementation has demonstrated its potential to efficiently optimize core design in power and advanced nuclear reactor applications. AI-driven solutions may optimize fuel loading patterns and extend fuel load duration. This could increase power output, minimizes waste production and reduces operational costs. Additionally, AI has the potential to support the design of advanced nuclear reactors and fuel cycle facilities by simulating complex physical processes, which could lead to improved designs and reduced development time. The development and deployment of AI solutions in the commercial nuclear power industry and fuel cycle facilities is expected to accelerate as experience accumulates and uncertainties are addressed.

AI is increasingly being used in the analysis of video data to help operational staff ensure safety at production and operational facilities. This applies to both the control mechanisms for personal protective equipment and the safety of personnel at the site

H.
Human Health

H. Human Health

H.1. Non-invasive Assessment of Gut Digestive Function: An Optimized Carbon-13 Sucrose Breath Test

Status

One of the most pressing public health nutrition questions is why children in low and middle income countries (LMICs) remain stunted (short for their age) despite multiple public health interventions, including food supplementation and improved water sanitation. The most recent joint report of United Nations agencies on food security and nutrition indicates that about 150 million children below five years of age are stunted, with dire implications for their psychomotor development and risk of chronic diseases later in life.[11] While factors related to stunting are complex and not fully understood, environmental enteric dysfunction (EED) — which is characterized by systemic and chronic disturbance of the structural integrity and function of the intestines — is increasingly implicated in stunting among children living in unsanitary settings in LMICs.[12] EED may contribute to stunting via various pathways, including increased gut permeability, inflammation and reduced nutrient absorption.[2] The diagnostic criteria for EED are poorly developed, and the most robust approach relies on invasive biopsy to diagnose gut damage. In most LMIC settings where EED is prevalent, this approach is neither viable nor ethically justifiable.

Breath tests, which have been used in human health applications such as gastroenterology, are non-invasive and can be used across all age ranges, including in children.[13] Common breath tests include hydrogen (H_2), methane (CH_4) and carbon-13 (^{13}C)-labelled carbon dioxide ($^{13}CO_2$). H_2 and CH_4 breath tests are performed mainly to assess general carbohydrate malabsorption.[3,14] On the other hand, ^{13}C breath tests are used to assess a plethora of symptoms in gastroenterology because they utilize selected ^{13}C-labelled molecules to target specific functions and measure $^{13}CO_2$ in breath as the end-product of metabolism. An established clinical application is the ^{13}C breath test to diagnose Helicobacter pylori using ^{13}C urea.[15] Nevertheless, breath test applications have largely been limited to clinical settings and have only seen limited use in public health nutrition.

The ^{13}C sucrose breath test (^{13}C-SBT) has previously been applied to study sucrose digestion in the context of congenital sucrase–isomaltase deficiency[16]. Breath $^{13}CO_2$ enrichment following the oral ingestion of ^{13}C sucrose reveals impairments in the capacity of the gut to digest sucrose, reflecting reduced activity of duodenal sucrase–isomaltase (the enzyme in the gut that must cleave sucrose into glucose and fructose before they can be absorbed and metabolized) (Figures H.1 and H.2). ^{13}C-SBT has also been used as a marker of added dietary

[11] Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme and World Health Organization. The State of Food Security and Nutrition in the World 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum, FAO, Rome (2023).

[12] Owino, V., et al., Environmental Enteric Dysfunction and Growth Failure/Stunting in Global Child Health, Pediatrics. 138 6 (2016).

[13] Broekaert, I.J., et al., An ESPGHAN Position Paper on the Use of Breath Testing in Paediatric Gastroenterology, Journal of Pediatric Gastroenterology and Nutrition. 74 1 (2022) 123–37.

[14] Hammer, H.F., et al., European guideline on indications, performance, and clinical impact of hydrogen and methane breath tests in adult and pediatric patients: European Association for Gastroenterology, Endoscopy and Nutrition, European Society of Neurogastroenterology and Motility, and European Society for Paediatric Gastroenterology Hepatology and Nutrition consensus, United European Gastroenterology Journal. 10 1 (2022) 15–40.

[15] Keller, J., et al., European guideline on indications, performance and clinical impact of 13C-breath tests in adult and pediatric patients: An EAGEN, ESNM, and ESPGHAN consensus, supported by EPC, United European Gastroenterology Journal. 9 5 (2021) 598–625.

[16] Robayo-Torres, C.C., et al., 13C-breath tests for sucrose digestion in congenital sucrase isomaltase-deficient and sacrosidase-supplemented patients, Journal of Pediatric Gastroenterology and Nutrition. 48 4 (2009) 412–8.

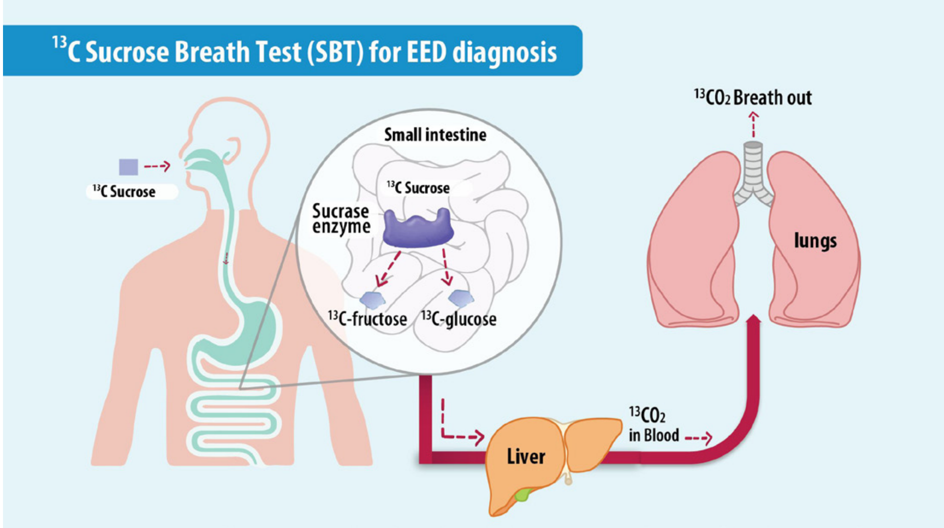


FIG. H.1. An individual consumes an accurately weighed dose of ^{13}C-labelled sucrose that is dissolved in a small amount of water. The ^{13}C sucrose is transported through the intestinal epithelium into the brush border, where it is hydrolysed by the enzyme sucrase–isomaltase into ^{13}C fructose and ^{13}C glucose, which are absorbed into the blood stream and transported to the liver, where they are broken down at varying rates to produce energy with the production of $^{13}CO_2$, which is exhaled in breath. The percentage of recovery of ^{13}C in $^{13}CO_2$ relative to the original ^{13}C in the labelled sucrose is an indication of the intestinal absorptive capacity and is correlated to sucrase–isomaltase activity. (Graphic: IAEA)

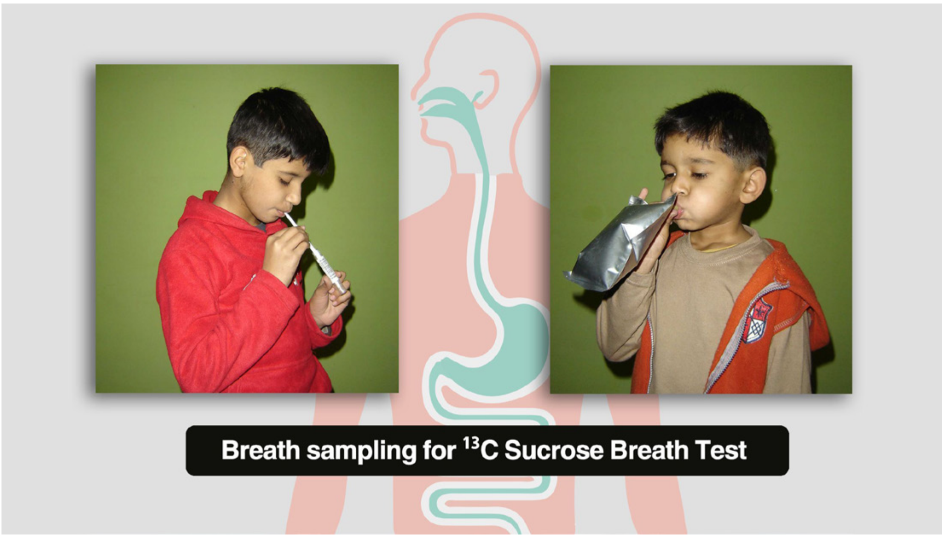


FIG. H.2. For older children and adults, breath is collected by breathing into a breath collection bag as shown. For infants and young children, a mask is fitted to the breath collection bag. (Graphic: IAEA)

sugar intake in rats.[17] Ritchie and colleagues were the first to apply ^{13}C-SBT to assess EED in Australian children with diarrhoea.[18] In that study, Aboriginal children with and without acute diarrhoea and a control group of healthy non-Aboriginal children received an oral dose of naturally enriched sucrose (from a maize source, which is slightly enriched in ^{13}C compared with beet sugar). $^{13}CO_2$ recovery after 90 minutes was lower in the Aboriginal children with diarrhoea

[17] Yazbeck, R., et al., Breath 13CO2-evidence for a noninvasive biomarker to measure added refined sugar uptake, Journal of Applied Physiology. 130 4 (2021) 1025–32.

[18] Ritchie, B.K., et al., 13C-Sucrose Breath Test: Novel Use of a Noninvasive Biomarker of Environmental Gut Health, Pediatrics. 124 2 (2009) 620–6.

compared to those without; the healthy non-Aboriginal children showed greater $^{13}CO_2$ recovery. However, this test is insensitive mainly because the ^{13}C signal from maize sucrose is not large enough over the natural and variable background of ^{13}C abundance (about 1.1%), even with very large doses of sucrose.[19,20]

Highly enriched sucrose (99%) can be used to improve the sensitivity of ^{13}C-SBT.[21] An Agency coordinated research project (CRP) entitled "Application of Stable Isotope Techniques in Environmental Enteric Dysfunction Assessment and Understanding its Impact on Child Growth" supported nine countries in optimizing and applying ^{13}C-SBT in EED assessment and understanding EED's impact on child growth. In the project's first phase,[22] the test was optimized and validated by comparing results from highly enriched sucrose tracers to naturally enriched sucrose in the United Kingdom. The optimized test was used in children with celiac disease in Australia and compared with biopsy results in Zambian adults and gut permeability testing in Peruvian children. In the project's second phase, the test was used in cross-sectional studies in Bangladesh, India, Jamaica, Kenya, Peru and Zambia to assess EED in children aged 12–15 months.

Trends

^{13}C-SBT is a non-invasive breath test intended to measure small intestinal damage in EED by using an oral dose of ^{13}C sucrose. Validation studies in the United Kingdom and Zambia showed that using a small dose of highly enriched ^{13}C sucrose could be applied to accurately assess brush border enzyme activity, specifically of sucrase–isomaltase activity present in the gut.[11] However, a limitation of the test is that the results were not directly linked to the underlying biological processes in the gut. Thus, researchers have been working on developing new mechanistic models to better understand the metabolic dynamics taking place in the gut.[23] These models have highlighted the importance of distinguishing between the metabolism of fructose and glucose present in ^{13}C sucrose. To better match the biological mechanisms involved in ^{13}C-SBT, it is recommended to use glucose ^{13}C-labelled sucrose. For more holistic results, ^{13}C-SBT can be applied alongside other tests to cover additional EED domains beyond sucrose digestion.

H.2. Assuring Quality: New Developments in Brachytherapy

Status

Cervical cancer continues to pose a significant challenge as the fourth most common cancer among women worldwide. In 2020, approximately 90% of new cases and fatalities occurred in LMICs[24]. The IAEA's Rays of Hope initiative aims to increase access to cancer care, with special focus on Africa, where 70% of the population lacks access to radiotherapy. In its first wave, Rays of Hope is focused on seven countries — Benin, Chad, the Democratic Republic of the

[19] International Atomic Energy Agency, New approaches for stable isotope ratio measurements Proceedings of an Advisory Group meeting held in Vienna, 20–23 September 1999, IAEA-TECDOC-1247, IAEA, Vienna (2001).
[20] Butler, R.N., et al., Stable Isotope Techniques for the Assessment of Host and Microbiota Response During Gastrointestinal Dysfunction, Journal of Pediatric Gastroenterology and Nutrition. 64 1 (2017) 8–14.
[21] Schillinger, R.J., et al., 13C-sucrose breath test for the non-invasive assessment of environmental enteropathy in Zambian adults, Frontiers in Medicine. 9 (2022).
[22] Lee, G.O., et al., Optimisation, validation and field applicability of a 13C-sucrose breath test to assess intestinal function in environmental enteropathy among children in resource poor settings: study protocol for a prospective study in Bangladesh, India, Kenya, Jamaica, Peru and Zambia, BMJ Open. 10 11 (2020).
[23] Brouwer, A.F., et al., Mechanistic inference of the metabolic rates underlying 13C breath test curves, Journal of Pharmacokinetics and Pharmacodynamics. 50 3 (2023) 203–14.
[24] Sung, H., et al., Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries, CA Cancer Journal for Clinicians. 71 (2021) 209–49.

Congo, Kenya, Malawi, Niger and Senegal — where cervical cancer ranks as either the most prevalent or the second most prevalent cancer among women. Rays of Hope will tackle the challenges associated with cervical cancer by raising awareness, providing training and capacity building, and increasing access to treatment and care.

FIG. H.3. Five inaugural Anchor Centres were formally established at a side event on the IAEA's Rays of Hope initiative, during the IAEA's 67th General Conference. (Photo: IAEA)

Treating cervical cancer requires a combination of surgery, chemotherapy and radiotherapy. Brachytherapy — a vital component of radiotherapy — plays a pivotal role in managing this disease, with modern brachytherapy supported by well-established evidence on the relationship between an administered dose and its clinical effect. However, since brachytherapy delivers significantly higher doses than external beam radiotherapy, it presents a unique treatment challenge: brachytherapy requires meticulous optimization to avoid adverse clinical effects from under- or over-dosage.

Ensuring consistent dose delivery is crucial to the quality and safety of this treatment option. This can also build public confidence in brachytherapy, which has been undermined by past reported incidents, including one fatality, that were attributed to human error. Dosimetry audits can prevent catastrophic incidents and minimize systematic dose variations.

Since its establishment in 1969, the Agency postal dosimetry audit programme has provided audit services through the Agency's Dosimetry Laboratory in various radiotherapy technologies to Member States lacking the capacity to do so at the national level. This critical service has significantly contributed to safe radiotherapy practices around the world, benefiting millions of cancer patients.

For brachytherapy, there is also a growing gap in education and training — one that is compounded by the technology's increasing complexity and the lack of training equipment. LMICs have little or no possibility to develop the needed human resources able to use this technique in a safe and effective manner.

The Agency is using virtual reality as an innovative tool to close this skills gap in a cost-effective manner. It has developed e-learning material on gynaecological brachytherapy procedures within a virtual reality-based, three-dimensional learning environment (Figure H.4). As an alternative to real patients, this technology enables trainees to practise brachytherapy, which helps to enhance the treatment and management of cervical cancer, especially in resource-challenged contexts.

FIG. H.4. The Agency's new e-learning module on gynaecological brachytherapy procedures for use with a virtual reality headset. (Photo: IAEA)

Trends

In 2021, the Agency launched a CRP entitled "Development of Methodology for Dosimetry Audits in Brachytherapy", which aims to develop a dosimetry audit methodology that will include three levels of complexity for auditing clinical practices. This methodology will benefit countries by ensuring the safe and effective treatment of gynaecological cancers. To date, a basic audit level assessing the accuracy of a crucial dosimetric parameter — the reference air kerma rate — has been developed. A simple, lightweight, and cost-effective phantom suitable for remote postal dosimetry audits was also created (Figure H.5).

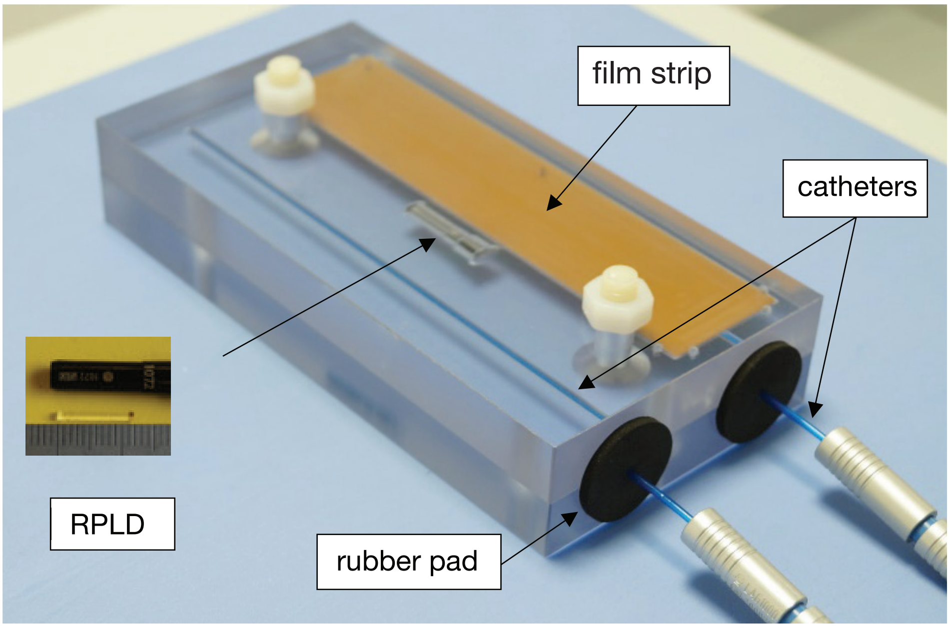


FIG. H.5. A simple, lightweight, cost-effective phantom developed in the Agency's Dosimetry Laboratory and used for brachytherapy audits (RPLD — radiophotoluminescent dosimeter). (Photo: IAEA)

The methodology has undergone testing in ten participating countries (Brazil, China, Croatia, Greece, India, the Islamic Republic of Iran, Mexico, the Russian Federation and South Africa, and the United Kingdom) that represent diverse clinical settings, ensuring the methodology's robustness. With such promising pilot results, a brachytherapy audit service will soon be available as part of the Agency postal dosimetry audit programme.

Ongoing research under the CRP also aims to develop a methodology for a more complex audit. Through an end-to-end audit, hospitals will be able to use their own applicators to complete the entire workflow of patient treatment. This development in turn will enhance confidence in brachytherapy's clinical practice, ensuring patient safety and treatment quality.

The benefits of the Agency's new virtual reality tool for brachytherapy education and training were demonstrated in an Agency workshop in Mozambique in July 2023. Professionals from the country were able to practise various processes related to gynaecological brachytherapy prior to the technique's clinical implementation (Figure H.6). Over 150 radiation oncologists, medical physicists, dosimetrists and radiation therapists from across Africa were also able to train with this tool at the Agency's e-contouring workshop at the African Organisation for Research and Training in Cancer's 14th International Conference on Cancer in Africa held in Senegal in November 2023.

FIG. H.6. A healthcare professional in Mozambique training in brachytherapy using the Agency's new virtual reality tool. (Photo: IAEA)

The Agency's virtual reality tool is an invaluable technology for enhancing access to high-quality training and interactive skills acquisition for health care professionals. It can help overcome physical, geographical and logistical constraints and catalyse the development of a highly skilled, professional cancer care workforce, ultimately contributing to global health and well-being.

H.3. Seeing Inside the Heart: The Crucial Role of Nuclear Imaging in Revealing Cardiac Amyloidosis

Status

Heart failure occurs when the heart has difficulty pumping blood effectively, leading to a deficiency of oxygen and nutrients in the body's tissues and organs. This can manifest in symptoms such as fatigue, shortness of breath and fluid retention. In severe cases, heart failure can give rise to life-threatening complications. Early detection and proper management play a pivotal role in improving outcomes and mitigating the risk of complications.

Heart failure is typically categorized into two main types based on their ejection fraction (EF), which indicates the age of blood expelled from the heart with each beat. For instance, an EF of 60% means that 60% of the heart's blood is pumped out with each contraction. While a normal EF typically ranges from 50% to 70%, this may vary slightly according to medical guidelines and the imaging modality used for measurement. An EF below the normal range indicates a reduced ability of the heart to pump blood effectively, which is a common feature in heart failure.

In heart failure with reduced ejection fraction (HFrEF), the heart muscle is weakened, and the heart is less efficient at pumping blood. People with this condition typically have an EF below 40%. In heart failure with preserved ejection fraction (HFpEF), the heart pumps normally, but the muscle is stiff and does not relax as it should in between beats. EF is normal or near-normal, usually equal to or greater than 50%. Because heart failure causes and management strategies vary, these classifications help guide treatment approaches. Heart failure, it should be noted, is a complex condition in which individual cases may have different underlying causes or contributing factors.

HFpEF often results from a combination of factors. Common contributors include high blood pressure, which can lead to the thickening and stiffening of the heart muscle; ageing, which can affect the heart's structure and function; diabetes, which can contribute to heart muscle stiffness; obesity, in particular excess body weight around the abdomen; and coronary artery disease, which reduces blood flow to the heart muscle due to the narrowing or blockage of the coronary arteries. An important contributing factor that has received increased attention in the past five years is transthyretin amyloid cardiomyopathy (ATTR-CMP), a disorder characterized by deposits of abnormal proteins (amyloids) in the heart tissue. It is estimated to affect 13–18% of adults over 65 with heart failure and has a median survival of 25–41 months.

Recent advancements in medical research and therapeutic strategies have ushered in a new era of hope for patients with cardiac amyloidosis. Innovative medications targeting the underlying mechanisms of amyloid deposition made available in early 2019 coupled with improved diagnostic imaging tools such as nuclear cardiology have enabled healthcare providers to intervene earlier and more effectively. This paradigm shift, driven by an evolving understanding of cardiac amyloidosis and the availability of treatments, represents a significant breakthrough in that it offers patients a more optimistic future. Despite these positive developments, the underdiagnosis of ATTR-CMP hinders the full utilization of these treatment breakthroughs.

Trends

Nuclear cardiology plays a pivotal role in evaluating cardiac amyloidosis. Through advanced imaging techniques such as technetium-99m pyrophosphate (99mTc-PYP) scanning, it allows for the precise detection of cardiac amyloidosis and its differentiation from other cardiac disorders. These imaging modalities provide valuable insights into myocardial involvement, aiding in early diagnosis and risk stratification (Figures H.7 and H.8). By assessing the extent and severity of amyloid deposition, nuclear cardiology assists clinicians in tailoring appropriate therapeutic interventions and monitoring disease progression. Moreover, the non-invasive nature of these techniques makes them particularly valuable for evaluating cardiac amyloidosis comprehensively, which in turns contributes to the more timely and accurate management of the condition.

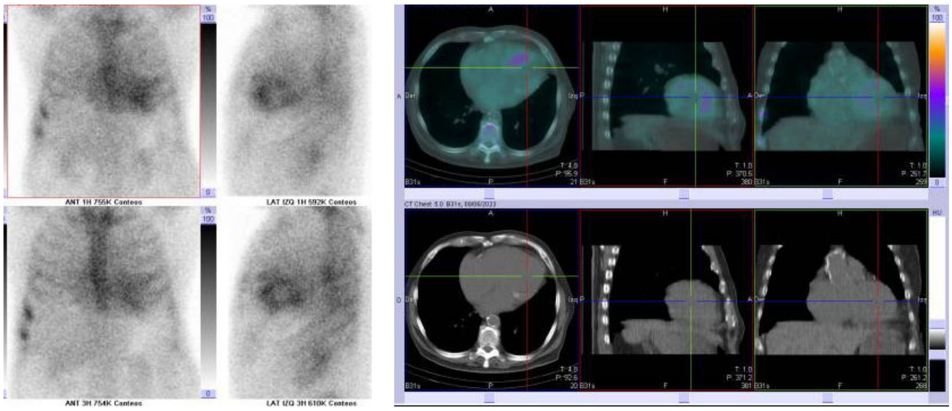


FIG. H.7. Anterior and lateral static images (left) and single photon emission computed tomography–computed tomography (SPECT–CT) images (right) of a patient with abnormal intense focal uptake of 99mTc-PYP in the myocardium, in keeping with ATTR-CMP. (Photos: A. Jiménez-Hefferman/Hospital Juan Ramón Jiménez)

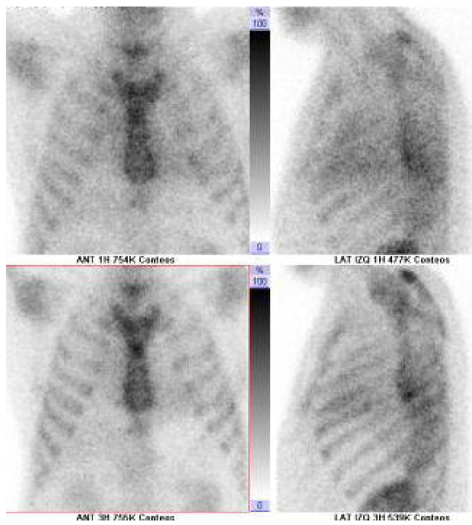


FIG. H.8. Anterior and lateral static images of a patient with no abnormal uptake of 99mTc-PYP in the myocardium, excluding ATTR-CMP as a cause of the patient's heart failure. (Photos: A. Jiménez-Hefferman/Hospital Juan Ramón Jiménez)

Although the technology and expertise for 99mTc-PYP SPECT exist, its practical use in diagnosing ATTR-CMP is limited in many countries. Since the condition's current diagnostic criteria were developed by experts in Europe and the United States of America, their validity for the ethnically and socio-economically diverse population of the rest of the world is unknown.

The Agency is conducting a CRP entitled "IAEA Transthyretin Amyloid Cardiomyopathy Study — The I-TAC Study", which aims to establish sustainable global proficiency in performing accurate PYP imaging to diagnose ATTR-CMP effectively. This will contribute to improving identification and treatment of HFpEF worldwide. In the quest for early detection and life-saving treatments, nuclear cardiology is emerging as a global beacon, illuminating a path to hope for people with cardiac amyloidosis.

I.

Food and Agriculture

I. Food and Agriculture

I.1. Irradiation Technologies for Vaccine Development: Applications of Nuclear Technologies to Prevent Infectious Diseases in Livestock

Status

Infectious diseases in the livestock industry can cause massive economic losses worldwide. For example, rinderpest epidemics have resulted in the death of many livestock animals globally for centuries, leading to continuous periods of food scarcity and widespread famine in rural regions, especially in Africa and Asia. In 2011, the world was declared free of this devastating illness thanks to the development of an effective vaccine and the implementation of widespread immunization programmes.

Vaccines are often a cost-effective approach for preventing diseases. There is a great need for faster design and production of vaccines against emerging and re-emerging pathogens, which are difficult to control and have the potential to cause devastating epidemics. This growing demand for safe vaccines to control priority diseases underscores the importance of evaluating new vaccine production platforms that require low-cost but efficient infrastructure. The traditional approach of vaccine manufacture, which involves inactivating pathogens, remains an efficient and rapid way for developing novel vaccines.

Currently, chemical inactivation is the predominant technique used in vaccine production. However, irradiation-induced inactivation offers many potentially significant benefits compared to chemical inactivation. The chemicals used for inactivation have the potential to modify essential pathogen proteins that are responsible for triggering immune responses. Irradiation inactivation, by contrast, preserves those proteins as well as the structural integrity of the pathogens, which helps provoke an immune response in the vaccinated individual upon exposure to the pathogen. However, irradiation inactivation does cause damage to the genetic material of the pathogen so that it lacks the ability to reproduce and cause infection. Although the technology has been in use for over 50 years, only recently has there been a resurgence of interest in using irradiation for vaccine production thanks to new irradiators that can provide precise radiation doses in shorter durations, along with an enhanced understanding of the immune system that enables more effective assessment of vaccination responses.

Over the past decade, the Agency, through the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, has made significant progress in this area, conducting research and development on the use of inactivation by radiation for vaccines against more than 20 animal and zoonotic pathogens. This research includes determining the right dose of radiation to kill the pathogens, setting parameters for vaccinations and discovering what happens post-vaccination.[25] For example, a prototype irradiated vaccine against influenza in chickens showed promising results when testing was done.[26]

[25] Cattoli, G., Ulbert, S. and Wijewardana, V., Editorial: Irradiation Technologies for Vaccine Development, Frontiers in Immunology, 9 January 2023.

[26] Alessio Bortolami, et al., Protective Efficacy of H9N2 Avian Influenza Vaccines Inactivated by Ionizing Radiation Methods Administered by the Parenteral or Mucosal Routes, Frontiers in Veterinary Science, Vol. 9, 11 July 2022.

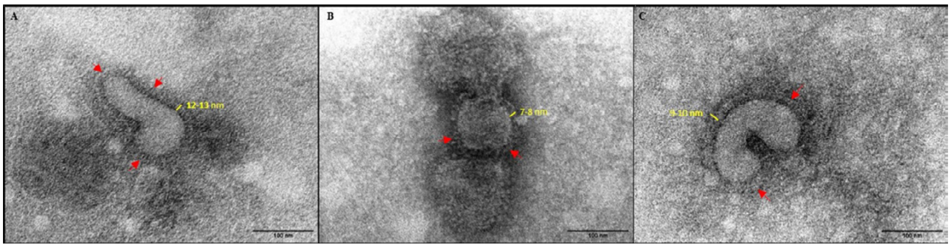


FIG. I.1. Characteristics of irradiated vs traditional chemically inactivated vaccines: A: live influenza virus; B: structurally damaged chemically inactivated influenza virus; and C: radiation-inactivated influenza virus that resembles the live virus structure so that, when immunized, a perfect memory of the pathogen is created in the vaccinated individual to fight the pathogen when exposed. Red arrows show the molecules that are responsible for inducing immunity within the vaccine candidate, while green lines show the length of those molecules. (Source: F. Bonfante/IZSVe, Italy and Frontiers in Veterinary Science, 11 July 2022)

Trends

In addition to its use in producing inactivated vaccines, irradiation can be employed to yield metabolically active but non-replicating organisms that can serve as potential vaccine candidates, particularly for bacterial and parasitic diseases. The radiation dosage can be adjusted to a level where microbes that are exposed to it cannot reproduce (i.e. cannot cause infection), while still maintaining their metabolic function. The advantage of this method is that an immune memory is created not only against the structure but also against the functions of the pathogen. This method was used to produce a vaccine against a nematode that infects the lungs of cattle and was subsequently introduced into the commercial market. Currently, this method is being explored in Sri Lanka through a CRP to produce an irradiated vaccine against a nematode that infects sheep and goats around the world.

Recent technical progress has enabled the utilization of electron beam and other irradiation methods to render pathogens inactive, allowing a shift away from the use of radioactive substances for producing irradiated vaccines using gamma radiation.

Furthermore, the use of novel radioprotectant substances such manganese ions (Mn^{2+}) and trehalose has resulted in improved preservation of the molecules of the pathogens responsible for immunity during irradiation inactivation.

Technological innovation has also improved processes for producing irradiated vaccines. One example is the use of a continuous thin fluid layer in the production of the electron beam inactivated vaccine developed by the Fraunhofer Institute in Germany and now being explored in Tunisia through a CRP to produce an irradiated vaccine against a nodavirus that affects seabass.

FIG. I.2. Scientists from Sri Lanka evaluate the immune response in a goat vaccinated with an irradiated vaccine against Haemonchus contortus, a nematode that can devastate flocks of sheep and goats, causing massive economic losses. (Photo: T. Anupama/University of Peradeniya, Sri Lanka).

I.2. Combining Cosmic Ray Neutron Sensor Nuclear Technology and Remote Sensing Imagery for Agricultural Water Management

Status

Three billion people living in agricultural regions experience high or very high levels of water scarcity. According to current Food and Agriculture Organization of the United Nations (FAO) projections, by 2050, about 57% of the global population could face water shortages for at least 1 month every year. Climate change will make this challenge even greater as extreme weather affects water availability for agricultural production through droughts or flooding. Therefore, having access to accurate and precise information on how these extreme effects impact soil moisture and crop water productivity is essential.

Monitoring soil moisture is crucial not only for irrigation management, but also for hydrological modelling, groundwater recharge, and flood and drought forecasting. Conventional and nuclear methods offer precise assessments of soil moisture at a localized level (e.g. a specific location in a field), whereas remote sensing technology provides comprehensive data on a broader scale.

Over the past ten years, there have been significant advancements in the development of the cosmic ray neutron sensor (CRNS). The Agency, through the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, has spearheaded this innovation with CRP entitled “Enhancing Agricultural Resilience and Water Security Using Cosmic Ray Neutron Sensor”. The CRP seeks to address the challenge of accurately measuring soil moisture by filling the gap between extensive satellite imaging and localized ground sensors for effective management of agricultural water usage. The CRNS operates by detecting low energy neutrons close to the soil’s surface, enabling the monitoring of soil moisture across large areas of up to 40 hectares. This technology has been refined, rendering it more accessible and cost-effective for both decision makers and farming communities. Consequently, its adoption is rapidly expanding among various stakeholders.

To maximize the impact of IAEA assistance to Member States through the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, the Atoms4Food initiative was launched by IAEA Director General Grossi, together with FAO Director-General Qu Dongyu, during the World Food Forum in Rome in October 2023 (Figure I.3). This initiative, coupled with new research and development efforts, is geared towards addressing the challenges posed by increasing food security needs and enhancing resilience to climate change worldwide.

FIG. I.3. Rafael Mariano Grossi, IAEA Director General and QU Dongyu, FAO Director General launched the Atoms4Food initiative during the World Food Forum in Rome on 18 October 2023. (Photo: IAEA)

Trends

Until recently, most CRNSs have been based on the use of proportional counting tubes, which typically use gases such as helium-3 or boron-10 trifluoride. While these counting tubes have a high sensitivity to neutrons (the proxy indicator for soil moisture), they are relatively expensive, which hinders the global transfer of this technology. Currently, however, detectors based on lithium and specific plastics and metallic materials are being used or tested by research institutions and commercial companies, causing a significant drop in prices since the development of such detectors in the early 21st century.

The CRNS technology is now being used together with high-resolution remote sensing imagery. The combination of nuclear and digital techniques allows for the monitoring of soil moisture across large areas in the landscape or at watershed level on a weekly basis. This cutting-edge technology has the potential to revolutionize remote sensing for climate-smart irrigation, which would significantly improve access to baseline information for decision makers and farming communities. This would enhance the sustainable use of water resources in agriculture, addressing SDG target 6.4, which aims to increase water use efficiency and fresh water supply.

This combination of nuclear and digital techniques is now, for the first time, being implemented in countries around the world to help conserve water resources for sustainable food production. In Africa, the technology has been introduced in 23 countries covering the continent's major land use types and climate zones, particularly those facing drought. This work also opens up a range of potential applications for environmental research, such as remote sensing data validation, soil moisture trend analysis, crop water productivity modelling, and changes in wetland water availability.

FIG. I.4: A CRNS installed in the high altitude Andean Bolivian wetlands to study their role in buffering water under climate change. (Photo: T. Franz, University of Nebraska–Lincoln)

In the Plurinational State of Bolivia, a CRNS was installed in the high altitude wetlands at around 4500 metres above sea level (Figure I.4). These wetlands are near the eternal snow of the 6088-metre-high Huayna Potosi mountain in the Cordillera Real, which has lost more than one third of its ice surface due to climate change, impacting the supply of water to millions of Bolivians. The device will help scientists to estimate the water buffering capacity of the wetlands, predict the extent and likelihood of droughts, and, in turn, support decision makers in developing climate change adaptation policies.

FIG. I.5: Training course on the use of CRNSs held in Seibersdorf, Austria under regional technical cooperation project RAF5086, "Promoting Sustainable Agriculture Under Changing Climate Conditions Using Nuclear Technologies (AFRA)". (Photo: IAEA)

Using training programmes and technology transfer, the Agency, through the Joint FAO/IAEA Centre, seeks to optimize and strengthen the capacities of countries for using this nuclear technique to achieve sustainable use of their water resources for food security (Figure I.5).

On 29 December 2023, the IAEA and Argentina signed a Memorandum of Understanding (MoU) aimed at enhancing cooperation in the area of food and agriculture through the newly launched Atoms4Food initiative (Figure I.6). Four priority areas have been identified in this MoU, covering food irradiation technology, animal health, the Sterile Insect Technique and identification of renewable carbon in bio-based products.

FIG. I.6: IAEA Director General Grossi (right) and Prof. Fernando Vilella, Director at Faculty of Agronomy, University of Buenos Aires, signed an MoU between the IAEA and the Secretariat of Food and Bioeconomy at the Ministry of Agriculture, Livestock and Fisheries of Argentina on cooperation in the area of the Atoms4Food initiative on 29 December 2023. (Photo: IAEA)

J.

Radioisotopes and Radiation Technology

J. Radioisotopes and Radiation Technology

J.1. Novel Delivery Systems for Cell Targeting Radiopharmaceuticals

Status

The use of radiopharmaceuticals is a safe and effective way to deliver radionuclides to organs, tissues or cellular targets of interest for either diagnostic or therapeutic purposes. Radionuclides should be delivered to the specific target and retained there for only as long as is necessary according to clinical requirements, avoiding accumulation and unnecessary radiation exposure in healthy tissues. Radioiodine, which has been used for the diagnosis and treatment of thyroid diseases since the early 1940s, was the first radionuclide to be used in this way. In addition, fluorine-18 sodium fluoride and radium-223/strontium-89 chlorides that are used in bone imaging and radionuclide therapy for bone metastasis respectively are other similar examples of simple radiopharmaceutical design. However, radiopharmaceutical use becomes more complex when designs involve different radionuclides that need to be tagged with various types of vectors, such as small molecules, peptides, antibodies and their fragments, which can precisely recognize cellular targets expressed on cancerous cells[27] (Figure J.1).

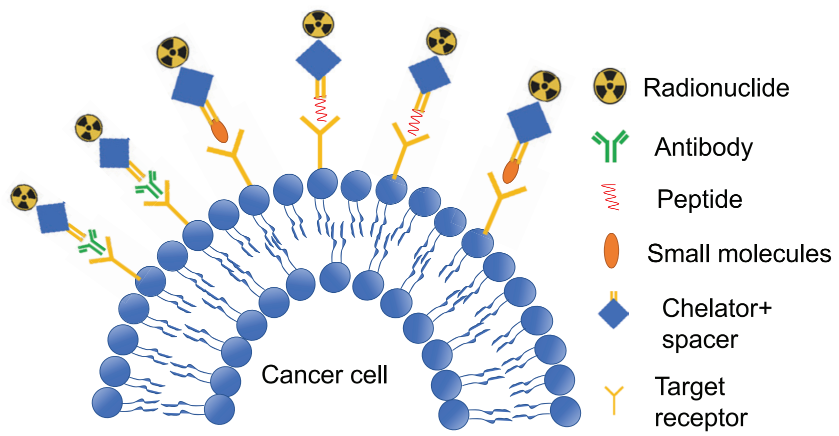


FIG. J.1. Schematic representation of radiopharmaceutical designs. (Graphic: IAEA)

Today, radiopharmaceuticals have proved their clinical utility not only for the functional imaging of organs, but also for the non-invasive visualization of cancer cells using target-specific radiopharmaceutical designs. This advancement allows for personalized treatment using novel medicines, including immunotherapeutics and therapeutic radiopharmaceuticals, such as those recently approved for prostate and neuroendocrine cancers.[28] Further treatment can be monitored using diagnostic radiopharmaceuticals.

Radionuclides with the appropriate physical properties for diagnostic imaging or therapy are increasingly available, thanks to technical developments and collaborative networks in multiple countries.[29] Biomedical research is also contributing to the development of molecules that can potentially be used for the radiolabelling of new disease-specific cell targets and pre-clinical developments. However, a bottleneck exists for clinical translation, owing to various challenges

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[27] *Bodei L., Herrmann K., Schöder H., Scott A. M. and Lewis J. S. Radiotheranostics in oncology: current challenges and emerging opportunities. Nature Reviews Clinical Oncology 19, 534–550 (2022).*

[28] *Food and Drug Administration web page: https://www.accessdata.fda.gov/scripts/cder/daf/index.cfm*

[29] *PRISMAP first publishable summary (PRISMAP, 2022): https://www.prismap.eu/members/repository/Public/Publishable_summaries/PRISMAP_PubSum_1.pdf*

associated with biological barriers and cellular level interactions that lead to degradation, metabolism and undesirable reactions that cause toxicity. The optimization of radiopharmaceutical formulations increases in complexity when radionuclides that decay with particulate emissions of short range beta, alpha and Auger electrons, without the associated gamma emissions suitable for imaging, are involved.

Trends

One way to overcome these radiopharmaceutical challenges is by using delivery systems that are similar to those used for non-radioactive pharmaceuticals and vaccines. Nano-delivery systems, including theranostic nano systems, with different permutations and combinations of imaging modalities, drugs and radionuclides, are being studied extensively, with the aim of enhancing the safety and efficacy of drugs. In biological systems, many of the internal mechanisms of a cell occur naturally at the nanometre scale (10–9 milli). Therefore, nanoparticle (NP) delivery is expected to provide numerous benefits, such as better therapeutic radionuclide concentration at the target with reduced side effects[30], through modifying the pharmacokinetics of drugs. NP delivery systems include different designs, such as dendrimers, liposomes, micelles, nanocapsules and nanospheres, as well as different types of NPs, such as inorganic, polymeric, solid lipid and others[31] (Figure J.2).

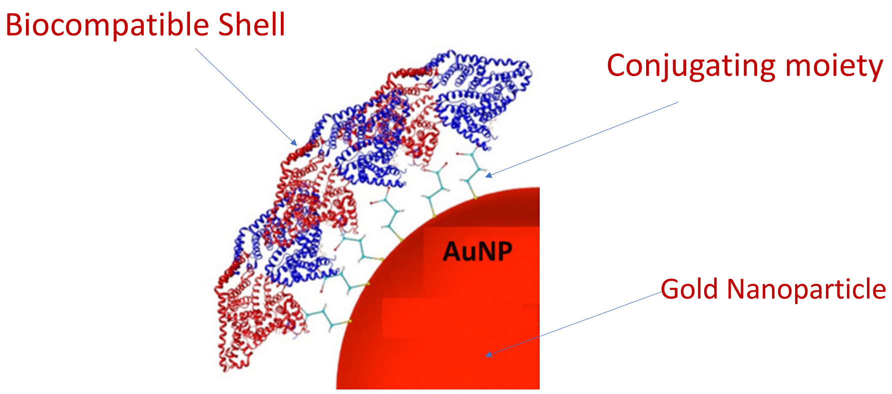


FIG. J.2. Schematics of a conjugated gold (Au) NP used in radiopharmaceutical development. (Graphic: IAEA)

Many radiopharmaceuticals currently under pre-clinical evaluation are based on antibodies, proteins or nanomedicines that have the potential to target the tumour micro-environment, either actively or passively. Better delivery systems are being developed as one method to explore the hidden potential of targeted radionuclide therapy. Click chemistry and bioorthogonal chemistry, which have received increased attention since the 2022 Nobel Prize in Chemistry was awarded to researchers working in these fields, have also been applied to radiochemistry and delivery systems, mainly for the effective delivery of radioimmunoconjugates (diagnostic or therapeutic radionuclides combined with specific immune substances).[32]

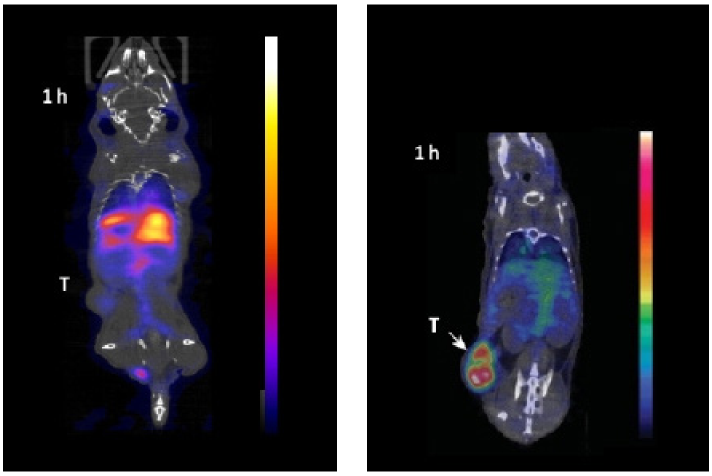
These targeted delivery systems can all be combined with pre-targeted approaches, chemotherapeutic combination therapies or radiation sensitizers.

[30] *Jani, P. Subramanian, S., Korde, A., Rathod, L. and Sawant, K. Theranostic Nanocarriers in Cancer: Dual Capabilities on a Single Platform. Functional Bionanomaterials Nanotechnology in the Life Sciences, 293 Thangadurai, D. et al. Functional Bionanomaterials. Nanotechnology in the Life Sciences, 293–310 (2020).*

[31] *Jalilian, A. R., Ocampo-García, B. et al. IAEA Contribution to Nanosized Targeted Radiopharmaceuticals for Drug Delivery, Pharmaceutics 14, 1060 (2022).*

[32] *Kondengadan, S. M., Bansla, S., Yang, C. et al. Click chemistry and drug delivery: A bird's-eye view. Acta Pharmaceutica Sinica B 13, 1990 (2023).*

Pre-targeted approaches have the potential to revolutionize modern theranostic strategies, as they can increase target-to-background ratios up to 150-fold, within early timeframes, as shown in Figure J.3. Initial results suggest that these approaches outcompete even conventional targeted radionuclide therapy approaches. The quicker achievement of higher target-to-background ratios and the pre-accumulation of antibodies allow radionuclides with short half-lives to be used, reducing the possibility that healthy tissue is exposed to radiation.



(a) (b)

FIG. J.3. Visualizations of the radioimmunoimaging of tumour-associated glycoprotein 72 targeting monoclonal antibody CC49 using the conventional approach (a) and the pre-targeting approach (b) for effective radiopharmaceutical delivery. (Source: Pharmaceuticals 15, 685 (2022)[33])

Future Agency activities will aim to bring together multidisciplinary experts in this field to determine the most promising systems, identify associated challenges and work out solutions for the clinical translation of these developments. A CRP has been planned for 2025 to assist Member States in their preparation for the smooth adoption of these developments towards the effective delivery of radiopharmaceuticals. The exchange of knowledge and technology transfer in the framework of the Agency is of great importance in this regard.

J.2. Radiotracer Technology and Constructed Wetlands for Mining Wastewater Recovery

Status

Although the mining and mineral processing industries contribute significantly to the global economy, they are also known to adversely affect the environment. The direct discharge of mining wastewater that contains organic and inorganic pollutants into the environment not only results in environmental pollution, but also wastes dwindling water resources. Consequently, recycling and reuse are essential to developing a circular economy in the mineral processing industry.

Conventional wastewater treatment systems have major limitations in their ability to remove recalcitrant pollutants present in various kinds of wastewater, as well as in relation to sludge accumulation, treatment and discharge. In addition to experiencing frequent breakdowns as a result of mechanical failure or mishandling, conventional wastewater treatment systems are expensive and personnel with a high level of technical proficiency are required throughout construction, operation and maintenance. Over the past decades, the Agency has facilitated industrial applications of radiotracer technology for the purpose of scrutinizing various wastewater treatment installations, such as mixers, aeration tanks, clarifiers, digesters and sedimentation and filtration units.

[33] *García-Vázquez, R., Battisti, U. M. and Herth, M. M. Recent Advances in the Development of Tetrazine Ligation Tools for Pretargeted Nuclear Imaging. Pharmaceuticals 15, 685 (2022).*

FIG.J.4. Wastewater generated from mining, Boinas valley, Belmonte de Miranda, Asturias, Spain. (Source: Adobe Stock)

Radiotracer technology plays an important role in the mineral processing industry, as it is used to study and troubleshoot processes in industrial plants, leading to greater optimization. Although the technology is applicable across a wide industrial spectrum, major target user groups include the petroleum and petrochemical industries, the mineral processing industry and the wastewater treatment industry. Radiotracer technology involves the use of sealed radioactive sources, open radioactive sources or nucleonic control systems, either alone or in combination, depending on the issue in question. In open source radiotracer technology, which is commonly used to study hydrodynamics, a radioactive tracer is injected into an industrial system. Radiation detectors and an integrated data acquisition system measure the tracer's activity at the system's exit, generating an exit age curve that can provide significant information about fluid flow.

Although radiotracer technology has helped to improve the efficiency of conventional wastewater treatment plants, there remains a demand for alternative methods that are easier to construct, operate and maintain. This demand has led to further advances in wastewater treatment that aim to overcome these persistent difficulties.

Constructed wetlands present an attractive alternative to conventional wastewater treatment plants. Constructed wetlands are engineered systems designed to use the natural functions of a wetland's plants, soils and microbial populations to treat contaminants in surface water, groundwater or waste streams. They are cost-effective and environmentally friendly systems, owing to their low energy consumption and simple mechanical infrastructure. Consequently, over the past five decades, constructed wetlands have emerged as a reliable treatment technology, suitable for all types of wastewater, including sewage, industrial and agricultural effluents, landfill leachate and stormwater run-off. Despite the advantages that constructed wetlands have over conventional wastewater treatment plants, knowledge and understanding of their complex hydrodynamics remains insufficient, making efficient operation and optimization of the treatment process a challenge. To overcome this gap, the Agency has launched a CRP that aims to develop a radiotracer method for constructed wetland studies, establish relevant protocols and guidelines and validate flow models for constructed wetlands.

FIG. J.5. A Conventional wastewater treatment system, Belarus. (Source: IAEA, modified graphic from Graphithèque/Adobe Stock)

Trends

The mining industry is expected to grow in the foreseeable future, as demand for new technologies that rely on critical materials continues to increase. Mine reclamation and closure plans, which depend on dwindling water resources, are important to the ultimate success of any mine. These plans consider all potential problems associated with both the mine and its wastewater treatment plant and may include some post-closure water treatment in addition to long-term sampling. The circular economy model has also recently gained attention as a way to address this complex scenario, encouraging the adoption of new technologies and processing strategies.

The effectiveness of using constructed wetlands for the removal of a variety of pollutants is well known. Nevertheless, research on constructed wetlands has mainly focused on biological and chemical treatment processes, using black box testing that compares influent and effluent pollutant concentrations, while disregarding the importance of flow characteristics, a key means of pollutant transport and removal, to overall system performance.

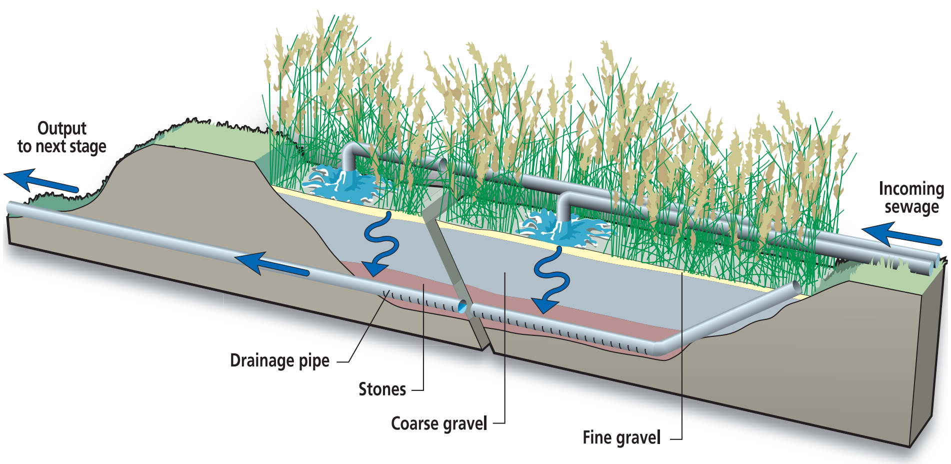


FIG. J.6. A schematic diagram of a constructed wetland. (Source: IAEA, modified graphic from Graphithèque/Adobe Stock)

A new Agency CRP on the hydraulic performance of constructed wetlands for mining wastewater recovery is being developed in order to investigate design parameters related to hydraulic processes and the interdependence of hydraulic processes and water quality processes using open-source radiotracer technology. This CRP will aim to develop models and tools that optimize the efficiency of pollutant removal in constructed wetlands through providing detailed spatial and temporal information, as well as to predict a wetland's dynamic response under a variety of conditions. The protocols and guidelines for the use of radiotracers in constructed wetlands developed in an existing CRP will be a great resource for the new CRP

K.

Isotope Hydrology

K. Isotope Hydrology

K.1. Tracing the Water Cycle: New Developments in Tritium Analysis

Status

Tritium is the only radioactive isotope incorporated into the water molecule, offering a valuable tracer for water cycle processes. Owing to its short half-life (12.3 years), tritium is mainly used in hydrology to estimate groundwater recharge and assess vulnerability to pollution. Tritium is produced naturally via cosmic ray interaction with nitrogen-14 in the upper atmosphere, with production rates of around 258 grams per year. Tritium is also produced as a by-product of the nuclear industry in quantities comparable to natural sources.

During the period 1945–1963, over 500 kilograms of tritium were released into the atmosphere as a result of the atmospheric testing of thermonuclear devices, resulting in a global increase of tritium several orders of magnitude over the natural level in precipitation. Since the ban on atmospheric testing in 1963, tritium levels in atmospheric waters have slowly decayed to steady-state levels. Owing to the low tritium concentration in contemporary natural waters, the measurement of tritium content has become technically challenging. In order to obtain sufficient decay counts for accurate and precise results suitable for reliable hydrological applications using commercial liquid scintillation counters, significant tritium enrichment is required (preconcentration of 15- to 100-fold).

Tritium enrichment is usually accomplished using alkaline electrolytic cells (AECs) with nickel–nickel or stainless–mild-steel electrodes, which were designed in the early 1960s. A recent Tritium Intercomparison proficiency test that took place in 2018 and involved around 90 laboratories revealed that over 75% of tritium laboratories worldwide use 250 mL or 500 mL mild-steel AEC systems to measure tritium in environmental water samples. However, nearly half of these laboratories produced inaccurate results for low and ultra-low levels of tritium in water samples, rendering these results unsuitable for hydrological applications. This poor performance was the result of either insufficient tritium enrichment or general problems with data postprocessing.

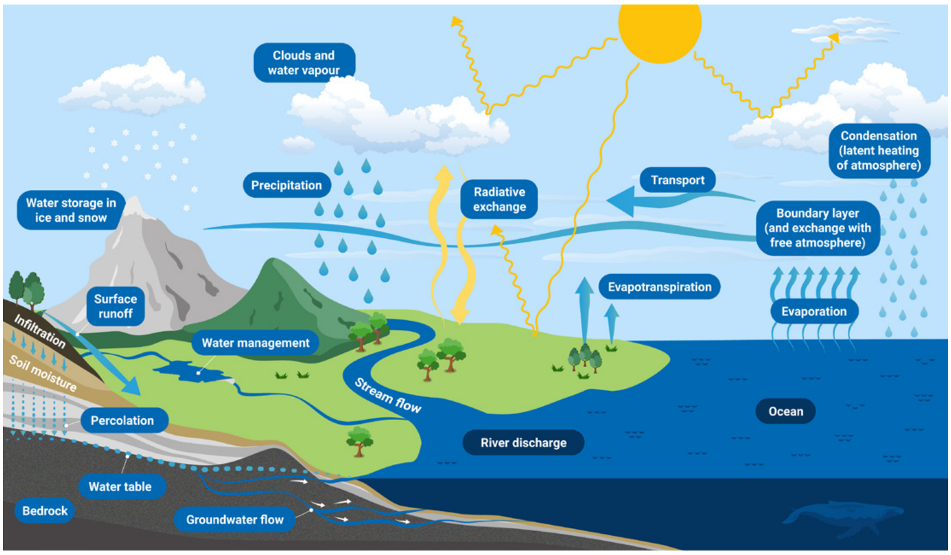


FIG. K.1. The water cycle. (Graphic: IAEA)

Trends

To address the need for higher tritium enrichment, the Agency's Isotope Hydrology Laboratory has developed and extensively tested an innovative polymer electrolyte membrane (PEM) system for tritium enrichment. This system promises to revolutionize the ability of Member States to determine the concentration of tritium in environmental water samples at ultra-low levels for both hydrological and radiological vigilance purposes.

The new tritium enrichment system can produce high preconcentration factors (more than 60-fold) and avoids some of the disadvantages of conventional tritium enrichment methods, including the use of hazardous electrolysis and neutralization chemicals and a complex electrolysis apparatus that requires extensive cooling and temperature controls. In addition, the new PEM system aims to simplify and shorten the analytical procedure, making the analysis of tritium a much easier task for Member States interested in using tritium as a tracer for the assessment and management of water resources.

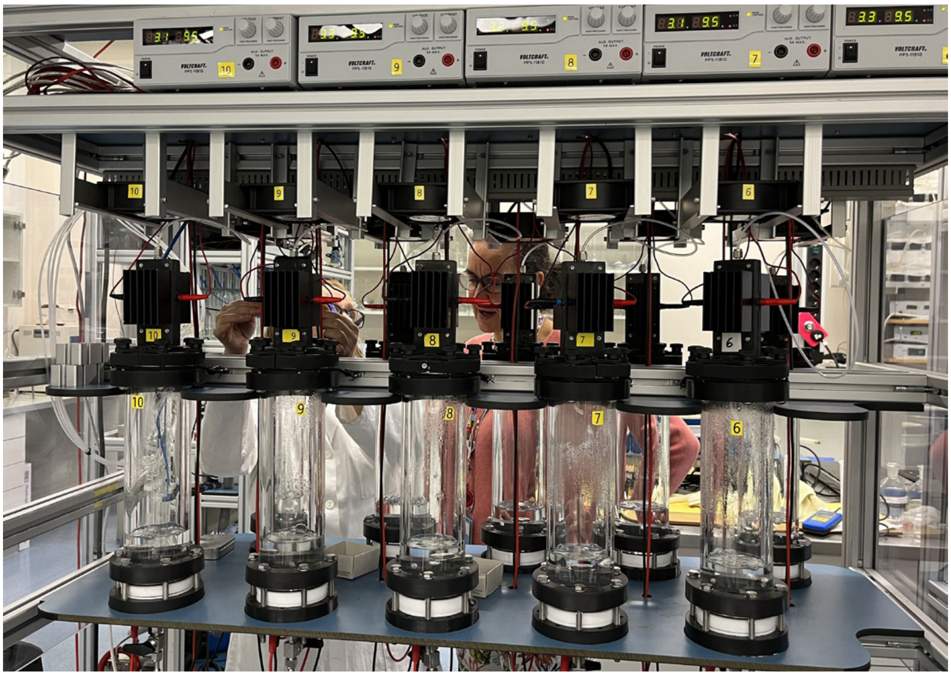


FIG. K.2. A front view of the Agency's PEM tritium system, consisting of ten electrolytic cells running a set of reference samples to test accuracy and precision. (Photo: IAEA)

Advances in tritium enrichment technology will help refine the discrimination of natural and anthropogenic signals and will increase the availability of natural tritium baseline data.

FIG. K.3. IAEA Director General Rafael Mariano Grossi delivers the opening statement of the Global Water Analysis Laboratory (GloWAL) Network launch event at the UN 2023 Water Conference in New York. (Photo: IAEA)

L.
Marine Environment

L. Marine Environment

L.1. Artificial Intelligence to Improve Monitoring and Research of Microplastic Pollution in the Ocean

Status

The influx of land-based plastic into the ocean has transformed marine environments into repositories of plastic waste. Marine ecosystems face a growing crisis, as an annual inflow of over 12 million tonnes of terrestrial plastic has resulted in the escalation of microplastic and nanoplastic pollution in the ocean. To address the dramatic increase in plastic pollution, the IAEA's NUclear TEChnology for Controlling Plastic Pollution (NUTEC Plastics) initiative is working to monitor microplastics and assess their impacts on marine environments. Despite advances in the understanding of marine plastic pollution, the quantification and characterization of microplastics remain difficult, owing to their intricate degradation processes and a lack of comprehensive polymer databases. As part of its research, NUTEC Plastics is working to build a globally available database of microplastics in various states of environmental degradation.

The IAEA is working closely with Member States in developing pilot scale plants for upcycling plastic waste into valuable products. Argentina, Indonesia, Malaysia and the Philippines have made great progress aiming to build technical scale prototypes in 2024, in cooperation with industrial partners. The main promising applications are focused on affordable, durable and high quality construction materials as well as radiation-assisted thermo-pyrolysis for fuel and additives production, and improved sleepers for railroads.

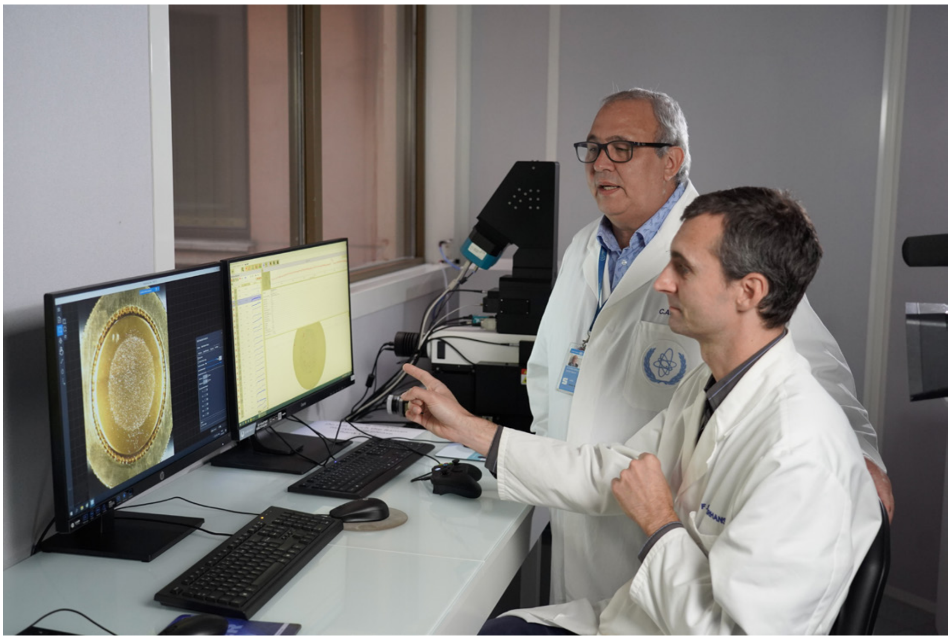


FIG. L.1. Scientists at the IAEA Marine Environment Laboratories analyse the chemical characteristics of microplastics in marine environmental samples using vibrational spectroscopy, Raman spectroscopy and Fourier transform infrared spectroscopy. (Photo: IAEA)

Several techniques that involve the interaction of photons with matter, such as Fourier transform infrared (FTIR) spectroscopy, Raman spectroscopy and laser direct infrared (LDIR) spectroscopy, have been used to detect and characterize polymers and microplastics. These methods rely on databases containing reference spectra, with which acquired particle spectra are compared. While reference spectra are typically derived from pristine polymers, particles in environmental samples rarely remain pristine and often undergo degradation as a result of factors such as ultraviolet light exposure and oxidation. This degradation alters the physicochemical properties of environmental samples, influencing their interaction with infrared light and resulting in modified spectral profiles, thereby increasing the risk of misidentification. Since compiling a database of polymer spectra at different stages of degradation would be a labour-intensive and impractical task, alternative approaches that combine faster analytical techniques and advanced data analysis methods to leverage existing information on both pristine and degraded samples are needed.

LDIR spectroscopy has recently emerged as an alternative technique at the IAEA Marine Environment Laboratories for the analysis of microplastics and polymers in samples of seawater, marine sediment and marine biota. Unlike techniques such as FTIR spectroscopy, LDIR spectroscopy offers the advantage of scanning samples before actual imaging and analysing only the areas where particles were detected. This results in faster analysis times, particularly for samples with minimal particle presence. However, one drawback is the potential erroneous identification of two adjacent particles as one, as only one spectrum is recorded per particle. Additionally, in comparison to other techniques such as FTIR spectroscopy, LDIR spectroscopy is more susceptible to misidentifications when analysing weathered particles, owing to the narrower infrared band recorded with LDIR instruments. Therefore, it is essential that more effective classification methods are developed in order to minimize the risk of misidentifications.

Trends

Machine learning can be a valuable tool for improving classification, although its application in the field of microplastic identification remains limited. Machine learning, including deep learning and reinforcement learning, has become integral to various scientific fields and industrial sectors, including biomedical engineering and water research. Machine learning involves training mathematical models to make predictions or decisions based on observed data, using methods derived from statistics and computer science. The application of machine learning to the identification of polymers and microplastics could therefore result in enhanced accuracy in environmental settings.

Artificial intelligence (AI) is emerging as a fundamental tool in the field of microplastic identification. AI's use of machine learning algorithms to unravel the complexities of degraded polymers in the marine environment represents a paradigm shift. The ability to generate spectra of degraded polymers under specific environmental conditions allows researchers to discern the typology of microplastics with unprecedented precision. This spectral insight not only facilitates discrimination among diverse plastic compositions, but also provides researchers with a profound understanding of both a polymer's origins and its behaviour in different marine settings.

FIG L.2 The Agency is currently engaged in a project that aims to analyse microplastics found in seawater and sediment samples collected in Antarctica in partnership with the Argentine Antarctic Institute. (Photo: IAEA)

The convergence of AI and environmental conservation has occurred at a crucial moment in the ongoing battle against marine plastic pollution. The speed of its spectral analysis, coupled with the simulation of physical, chemical and biological processes to generate spectra of degraded polymers, position AI as a sophisticated lens through which to view and overcome the complex challenges posed by microplastic pollution. As we continue to navigate the intersection of technological innovation and environmental management, AI promises to be a formidable tool in the fight for a plastic-free ocean.

■ Annex

Table A-1. Nuclear power reactors in operation and under construction in the world[a]

COUNTRY	Reactors in Operation		Reactors in Suspended Operation		Reactors Under Construction		Nuclear Electricity Supplied	
	No. of Units	Total MW(e)	No. of Units	Total MW(e)	No. of Units	Total MW(e)	TW(e).h	Nuclear Share %
ARGENTINA	3	1 641			1	25	9.0	6.3
ARMENIA	1	416					2.5	31.1
BANGLADESH					2	2 160		
BELARUS	2	2 220					11.0	28.6
BELGIUM	5	3 908					31.3	41.2
BRAZIL	2	1 884			1	1 340	13.7	2.2
BULGARIA	2	2 006					15.5	40.5
CANADA	19	13 699					83.5	13.7
CHINA	55	53 152			24	24 948	406.5	4.9
CZECH REP.	6	3 934					28.7	40.0
EGYPT					3	3 300		
FINLAND	5	4 394					32.8	42.0
FRANCE	56	61 370			1	1 630	323.8	64.8
HUNGARY	4	1 916					15.1	48.8
INDIA	19	6 290	4	639	8	6 028	44.6	3.1
IRAN, ISL.REP	1	915			1	974	6.1	1.7
JAPAN	12	11 046	21	20 633	2	2 653	77.5	5.5
KOREA, REP.OF	26	25 825			2	2 680	171.6	31.5
MEXICO	2	1 552					12.0	4.9
NETHERLANDS, KINGDOM OF THE	1	482					3.8	3.4
PAKISTAN	6	3 262					22.4	17.4
ROMANIA	2	1 300					10.3	18.9
RUSSIA	37	27 727			3	2 700	204.0	18.4
SLOVAKIA	5	2 308			1	440	17.0	61.3
SLOVENIA	1	688					5.3	36.8
SOUTH AFRICA	2	1 854					8.2	4.4
SPAIN	7	7 123					54.4	20.3
SWEDEN	6	6 944					46.6	28.6
SWITZERLAND	4	2 973					23.4	32.4
TÜRKIYE					4	4 456		
UAE	3	4 011			1	1 310	31.2	19.7
UK	9	5 883			2	3 260	37.3	12.5
UKRAINE	15	13 107			2	2 070	NA	NA
USA	93	95 835			1	1 117	742.4	18.5
Worldwide[b,c]	**413**	**371 539**	**25**	**21 272**	**59**	**61 091**	**2 508.7[c]**	**N/A**

Note: NA — Not Available, N/A — Not Applicable.

[a] Source: Agency's Power Reactor Information System (PRIS) (www.iaea.org/pris) as per data provided by Member States by 16 June 2024.

[b] The total figures include the following data from Taiwan, China: 2 units, 1 874 MW(e) in operation and 17.2 TW·h of electricity supplied, accounting for 6.9% of the total electricity mix.

[c] The total electricity production does not include Ukraine as operational data was not submitted for the year 2023.

Table E-1. Common applications of research reactors worldwide

Type of application[a]	Number of research reactors involved[b]	Number of Member States hosting such facilities
Teaching/training	162	51
Neutron activation analysis	119	50
Radioisotope production	83	40
Neutron radiography	69	34
Material/fuel irradiation	67	26
Neutron scattering	45	28
Geochronology	25	22
Transmutation (silicon doping)	24	15
Transmutation (gemstones)	21	12
Neutron therapy, mainly R&D	16	11
Nuclear data measurement	17	11
Other[c]	116	35

[a] The Agency publication Applications of Research Reactors (IAEA Nuclear Energy Series No . NP-T-5 .3, Vienna, 2014) describes these applications in more detail.

[b] Out of 234 research reactors considered (225 in operation, 9 temporarily shut down, as of December 2023).

[c] Other applications include calibration and testing of instrumentation, shielding experiments, creation of positron sources and nuclear waste incineration studies.

List of Abbreviations and Acronyms

^{13}C-SBT	^{13}C sucrose breath test
^{99m}Tc-PYP	technetium-99m pyrophosphate
AEC	alkaline electrolytic cell
AI	artificial intelligence
ARAO	Slovenia's Agency for Radwaste Management
ATF	advanced technology fuel
ATTR-CMP	transthyretin amyloid cardiomyopathy
CFS	Commonwealth Fusion Systems
CIRES	Industrial Facility for Grouping, Sorting and Disposal
COP28 2023	Conference of the Parties to the United Nations Framework Convention on Climate Change
COVID-19	coronavirus disease 2019
CRNS	cosmic ray neutron sensor
CRP	coordinated research project
CT	computed tomography
DAQ	detector data acquisition
DEMO	demonstration fusion power plant
DTT	Divertor Tokamak Test
EED	environmental enteric dysfunction
EF	ejection fraction
FAO	Food and Agriculture Organization of the United Nations
FTIR	Fourier transform infrared
FPGA	field programmable gate arrays
GJ	gigajoules
GW	gigawatt
GW(e)	gigawatt (electrical)
HALEU	high assay low enriched uranium
HEU	high enriched uranium
HFpEF	heart failure with preserved ejection fraction
HFrEF	heart failure with reduced ejection fraction
HPR1000	Hualong One
HTGR	high temperature gas cooled reactor
HTTR	High Temperature Engineering Test Reactor
IFMIF	International Fusion Materials Irradiation Facility
INIR	Integrated Nuclear Infrastructure Review
INL	Idaho National Laboratory
JET	Joint European Torus

keV	kiloelectronvolt
LDIR	laser direct infrared
LEU	low enriched uranium
LFR	lead cooled fast reactor
LIDAR	light detection and ranging
LILW	low and intermediate level waste
LLNL	Lawrence Livermore National Laboratory
LMICs	low and middle income countries
LTO	long term operation
LWR	light water reactor
MARVEL	Microreactors Applications, Research, Validation and Evaluation
MeV	megaelectronvolt
MHTGR	modular high temperature gas cooled reactor
MIT	Massachusetts Institute of Technology
ML	machine learning
MMR	Micro Modular Reactor
MSFR	molten salt fast reactor
MSR	molten salt reactor
MW(e)	megawatt (electrical)
NHSI	Nuclear Harmonization and Standardization Initiative
NIF	National Ignition Facility
NORM	naturally occurring radioactive material
NP	nanoparticle
NPP	nuclear power plant
NPPA	Nuclear Power Plants Authority
NRAD	Neutron Radiography Reactor
NRC	Nuclear Regulatory Commission
OECD/NEA	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development
PET	positron emission tomography
PEM	polymer electrolyte membrane
PRIS	Power Reactor Information System
PWR	pressurized water reactor
R&D	research and development
SCWR	supercritical water cooled reactor
SFR	sodium cooled fast reactor
SMART	system-integrated modular advanced reactor

SMRs	small and medium sized or modular reactors
SNF	spent nuclear fuel
SPECT–CT	single photon emission computed tomography–computed tomography
STEP	Spherical Tokamak for Energy Production
t HM	tonnes of heavy metal
TLAA	Time Limited Ageing Analysis
TW · h	terawatt hour
UGV	uncrewed ground vehicles
UKAEA	United Kingdom Atomic Energy Authority
WCR	water cooled reactor
WHO	World Health Organization

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