Nuclear Technology Review ■ 2025

Report by the Director General

IAEA

GC(69)/INF/9

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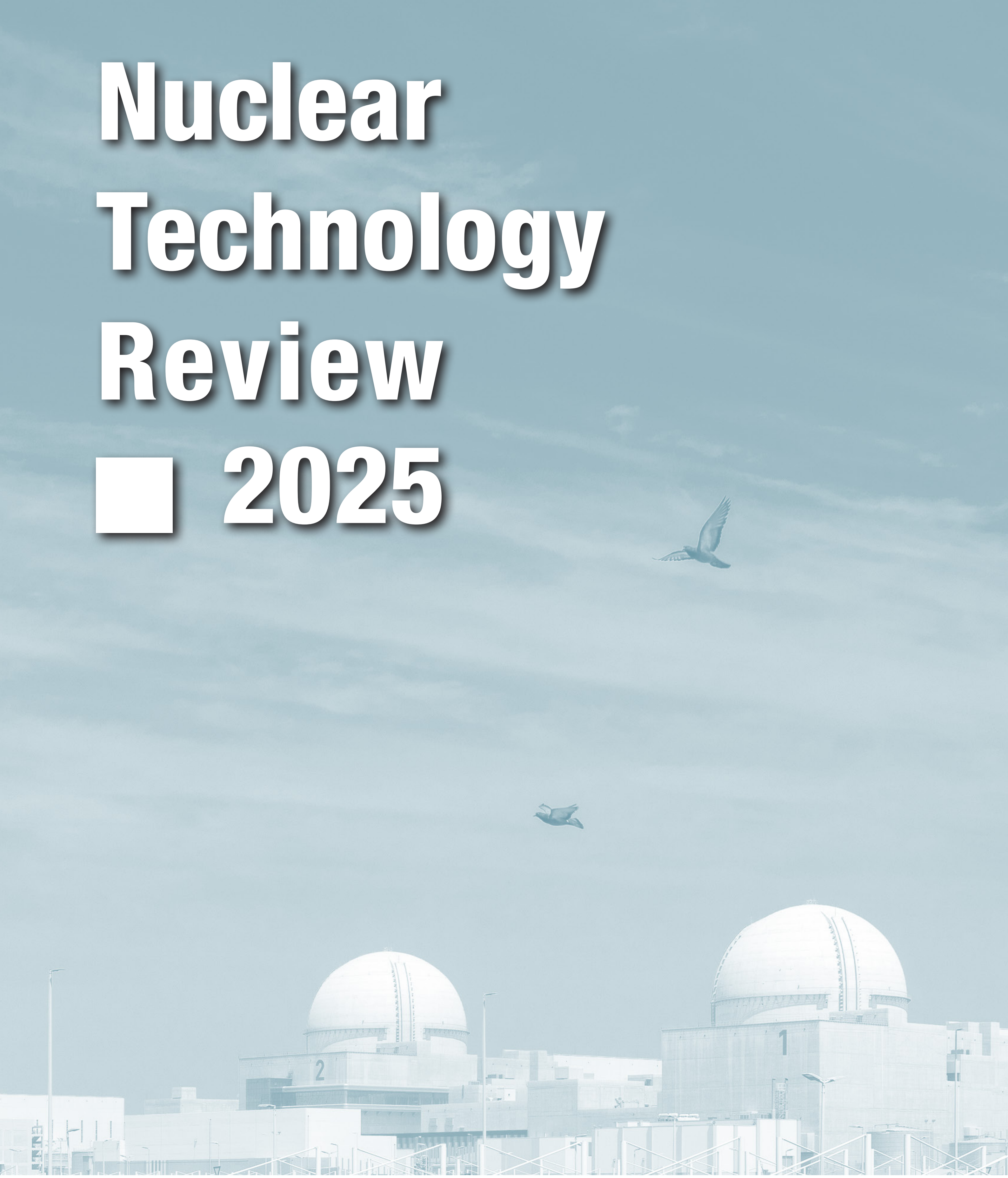

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- In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* each year. Attached is this year's report, which highlights notable developments in 2024.

- The Nuclear Technology Review 2025 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, application of 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 2025 session of the Board of Governors in document GOV/2025/4. 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

The Agency's statutory objective to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" holds today as never before. Be it the availability of lighting and heating in homes, access to cancer screening and timely treatment, the availability of crops that can withstand changing climate conditions, or access to clean water — nuclear power and nuclear techniques play an important role in addressing these challenges.

The political momentum for nuclear power witnessed at the 28th Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in 2023 — as reflected in the call to accelerate nuclear power deployment included in the first Global Stocktake, and the call by 22 (subsequently 25) countries to triple nuclear capacity by 2050 — continued throughout the year. In March 2024, the first ever Nuclear Energy Summit, co-hosted by the Government of Belgium and the Agency in Brussels, brought together Heads of State and ministers from around 30 countries, as well as industry leaders and other stakeholders. In September, the Agency published its updated nuclear capacity projections to 2050, with an increased high case projection of 950 gigawatts (GW) — an increase of 2.5 times the current capacity. Although ambitious, this target could be realized through favourable policy frameworks, increased access to financing and the commercialization of small modular reactors (SMRs), which could represent nearly a quarter of the new build projects needed to reach the high case projection. Moreover, the Agency consistently supported the agenda of Brazil's G20 Presidency to include nuclear as part of energy transition discussions, as reflected in the G20 Ministerial Declaration. At the 15th Clean Energy Ministerial, also held in Brazil, the Agency released its flagship publication *Climate Change and Nuclear Power 2024: Financing Nuclear Energy in Low Carbon Transitions.* Lastly, at COP29, the Agency, its partners and several Member States highlighted the importance of accelerating the deployment of nuclear power plants, including SMRs, as one of the key mitigation actions to keep the objective of limiting global warming to 1.5 degrees Celsius within reach. Six additional Member States joined the call to triple nuclear power by 2050.

Financing the deployment of nuclear technology will be key to ensuring that nuclear power can play its full role in contributing to the decarbonization of our energy systems. And it is clear from the Agency's analysis that although governments must continue to play an important role, the private sector and multilateral development banks will also be essential in this regard. In September, on the margins of Climate Week NYC, 14 large commercial banks and financial institutions pledged support for financing the tripling of nuclear power by 2050, confirming that nuclear is becoming an investable asset. The Agency has initiated high level discussions with multilateral development banks, including the World Bank and the European Bank for Reconstruction and Development, on financing nuclear developments.

Nuclear technologies provide solutions for critical global challenges. In cancer care, the Agency leads initiatives such as the Lancet Oncology Commission on Radiotherapy and Theranostics to assess needs and inform decision makers.

In food security, we offer easy-to-deploy techniques to detect and trace contaminants in the food supply chain, verify food authenticity and diagnose diseases affecting crops or cattle, thereby empowering Member States to protect livelihoods sustainably. The Agency's work advances environmentally friendly solutions, from using ionizing radiation, to create bioplastics and eco-friendly materials, to applying non-destructive testing, which is also becoming increasingly relevant in the context of additive manufacturing. We support efforts to monitor groundwater resources and prevent pollution, which are crucial as populations face displacement.

Marine protection is another priority, with our Monaco laboratories equipping Member States to safeguard marine ecosystems. Similarly, the Seibersdorf and Vienna laboratories drive knowledge transfer across sectors.

Our flagship initiatives — Atoms4Food, Nuclear Technology for Controlling Plastic Pollution (NUTEC Plastics), Rays of Hope, and Zoonotic Disease Integrated Action (ZODIAC) — exemplify how nuclear science and technology enhance the wellbeing of people and the planet.

For decades, nuclear science, technology and applications 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 2024, the *Nuclear Technology Review 2025* will help Member States make informed decisions when addressing both current and new challenges.

FIG. FW.1. IAEA Director General Rafael Mariano Grossi speaking at COP29 in Baku, Azerbaijan. (Photo: IAEA)

Executive Summary

For the fourth consecutive year, the Agency has revised upwards its annual projections for installed nuclear power capacity in the coming decades, reflecting the momentum behind its inclusion in the Global Stocktake concluded at COP28 and the pledge by 31 countries to triple global nuclear capacity by 2050, and the holding of the first ever Nuclear Energy Summit in Brussels in March 2024. In its new outlook for global nuclear capacity for electricity generation, the Agency has increased its high case projection to 950 gigawatts (electrical) (GW(e)) by 2050, representing 2.5 times the current installed capacity, with SMRs contributing approximately one quarter of that. In the low case projection, installed nuclear capacity would increase to 514 GW(e) by 2050, still a 40% increase compared to current installed capacity.

As of the end of December 2024, global operational nuclear power capacity was 377 GW(e), provided by 417 reactors across 31 Member States. In addition, 23 reactors licensed for operation, with a total capacity of 19.7 GW(e), were in suspended operation during 2024. Five pressurized water reactors (PWRs) and 1 pressurized heavy water reactor (PHWR), with a total capacity of 6.8 GW(e), were connected to the grid in five different Member States. At the end of December 2024, 62 reactors with a total capacity of 64.5 GW(e) were under construction across 15 countries. Two hundred and ninety-six of the reactors in operation representing approximately 66% (263.3 GW(e)) of the total installed capacity, have been in operation for over 30 years. Of those, 166 reactors representing approximately 34% (135.5 GW(e)) of the total installed capacity — have been in operation for over 40 years. The ageing fleet highlights the need for new or uprated operating nuclear capacity in order to offset planned retirements to continue contributing to sustainability, global energy security and the achievement of climate change objectives.

Currently, 37 countries are in various phases of initiating or implementing their national nuclear power programmes they are working on pre-feasibility studies, developing infrastructure or already constructing their first nuclear power plants (NPPs). Of those, 23 countries are in the decision-making phase, and 14 countries are in the post-decision-making phase. In addition, some 20 countries are interested in nuclear power and are looking into its inclusion in their future energy mix.

Water cooled reactors (WCRs) continued to be the predominant technology used in NPPs worldwide. Current trends involve enhancing the safety features of WCRs, including through more passive cooling systems and improved fuel designs. SMRs continue to be considered worldwide for a range of applications. The current trend in SMR development focuses on improving their economics, safety features and scalability. There is also growing interest in SMRs for maritime applications, including transportable floating power units and reactors used in civilian naval nuclear propulsion.

Non-electric applications of nuclear energy have been implemented for many years and their development continues. Currently, about 70 reactors are used for non-electric applications such as industrial process heating, district heating and desalination. Several SMR designs (including one already in operation) allow for their possible use for non-electric applications.

Regarding fast reactor technology development, the current focus is on improving safety measures by incorporating passive shutdown systems and on further exploring different types of coolant, particularly in the context of innovative reactor designs. There is also a strong emphasis on improving the economics of fast reactors, including through the reduction of construction costs and the enhanced integration of fast reactors with closed fuel cycle technology.

Machine learning and artificial intelligence (AI) techniques are increasingly applied to improve quality and performance in the nuclear industry. These applications may improve safety, operational efficiency and cost-effectiveness while also facilitating the development of advanced nuclear technologies. AI-based systems are being introduced in the context of other trends, such as increased digitalization and the adoption of robotic and drone-based systems at NPPs. However, a suitable method is needed to demonstrate that AI implementation does not compromise the overall safety of the NPP. AI is also used to optimize reactor core designs and fuel loading patterns. It is also worth noting that the use of nuclear energy to power data centres needed to accommodate computational demands of AI is expanding rapidly to deal with the unprecedented growth in energy demand in these areas.

In the area of fusion energy, governments across the globe are increasingly recognizing the potential of this technology and are stepping up investments in research and development (R&D) to propel scientific and technological progress. National strategies are being crafted — accompanied by substantial funding allocations — to support both public and private sector initiatives, the development of initial regulatory frameworks and increased engagement with supply chains. The fusion energy industry has now attracted more than US $8 billion in investment (up from US $6.21 in 2023). Regulatory bodies and lawmakers are increasingly addressing the challenges and opportunities presented by fusion energy.

According to the publication *Uranium 2024: Resources, Production and Demand* (Red Book 2024), published jointly by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) and the Agency, global uranium mine production increased by 9% in 2023 to 54 345 tonnes of uranium (tU). (Global forecasts indicate that, by 2050, uranium demand could range from 99 485 tU (low-demand scenario) to 142 695 tU (high-demand scenario) per year. Planned and prospective mines in 19 countries could contribute to a global total nominal production capacity of 80 494 tU annually. Hence, the assurance of uranium supply is likely to require that idled mines come back online and that planned and prospective mine projects be realized, considering that the discovery of new deposits will require that the current favourable market conditions be sustained. Indeed, in January 2024, the uranium spot price hit a 17-year high of US $106/lb U3O8 (US$275/kgU), and since mid-2024, it has been fluctuating between US$80/lb U3O8

(US $208/kgU) and US $85/lb U3O8 (US $221/kgU). This substantial price increase from the relatively flat 2016–2021 market prices of around US $20–30/lb U3O8 (US $52–78/kgU) could drive investment in further exploration.

Over the next decade, nuclear fuel production will face increasing demand due to the projected substantial increase in construction programmes in both established and embarking countries. The development of new fuel types, including for SMRs and other advanced reactors, will drive investment in the sector. Many designs for advanced technology/accident tolerant fuels (ATFs) and innovative fuel under consideration will require uranium enrichment above 5%; therefore, LEU+ and HALEU will be required.

Spent nuclear fuel (SNF) is accumulating in storage at a rate of approximately 7 000 tonnes of heavy metal (t HM) per year globally, and the stored inventory is more than 300 000 t HM. For countries with established nuclear programmes pursuing open cycle strategies, the main challenges remain the requirement for additional SNF storage capacities and the increasing storage duration prior to disposal. For countries pursuing closed cycle strategies, the main challenges are limited reprocessing capacities and the industrial-scale implementation of multi-recycling in light water reactors (LWRs).

The number of NPPs and research reactors actively undergoing dismantling continues to increase, with a trend towards early dismantling shortly after permanent shutdown. As of November 2024, 211 power reactors across 21 Member States were shut down for decommissioning, with 23 power units fully decommissioned. A recent development in NPP decommissioning is the rise of specialized consortia that combine expertise from multiple companies to implement complete decommissioning projects.

Emerging trends in environmental remediation of radioactively contaminated sites indicate the prioritization of sustainable practices, such as the application of circular economy principles to reduce remediation-generated waste and enhance resource efficiency. Technologies like remote sensing, machine learning and robotics play a significant role, enabling more accurate site and waste characterization, enhanced monitoring and safer waste management.

Significant progress in radioactive waste management worldwide continued throughout 2024, with notable advancements in disposal programmes and the application of predisposal technologies. These efforts underscore a commitment to long term waste management solutions that prioritize safety and environmental protection.

There were 234 operational nuclear research reactors, including those in temporary shutdown, in 54 countries at the end of 2024. In addition, 11 new research reactors were under construction in 10 countries and 13 Member States had formal plans to construct such reactors. The growing global interest in nuclear power has led to increased demand for access to research reactor infrastructure for the purpose of material and components testing, R&D and nuclear education and training. Demand for research reactor applications has also grown worldwide. Ion beam accelerators continue to play a key role in R&D related to cancer therapy, the hardening of electronic devices, dosimetry in the mixed radiation environment, shielding to mitigate radiation exposure, improving understanding of the biological effects of space radiation, and space exploration. Furthermore, recent advancements in neutron and gamma ray detector technology have led to compact, energy-efficient, dual-functional systems that facilitate hydrogen mapping and elemental analysis on celestial bodies, such as the Moon and Mars.

Cancer remains a leading cause of death worldwide, claiming 9.74 million lives and resulting in 19.98 million new cases in 2022. Despite nearly half of all cancer patients requiring radiotherapy at some point, access to this life-saving treatment is limited. To address this, the Agency led a Lancet Oncology Commission on Radiotherapy and Theranostics, to examine radiotherapy availability.

The Agency is also conducting research on spatially fractionated radiation therapy, an innovative technique for treating large and radioresistant tumours by delivering non-uniform radiation doses across tumour volumes. This approach allows for safe dose escalation, enhancing tumour monitoring and improving patients' quality of life through pain relief.

Protecting consumers from potentially harmful agrochemicals such as veterinary drugs and pesticides and facilitating fair global trade require harmonized standards such as the Codex Alimentarius maximum residue limits. Establishing these standards requires data on how these chemicals are absorbed, distributed, metabolized and excreted in food animals. This information can be used to determine the withdrawal period during which food products are safe for consumption following the last administration of the drugs.

Cyclotrons can be used not only for producing radioisotopes for diagnostics and radiotherapy, but also to support research aimed at enhancing national food safety systems.

The Agency has developed the first in a series of innovative methods using elemental analyser–isotope ratio mass spectrometry, which provides a faster and more accessible method for verifying food authenticity. This is especially important for foods with geographical identification that are often substituted by counterfeit versions.

The early detection of plant pathogens is crucial to curtail the spread of diseases and minimize crop damage. For effective prevention and control, early diagnostics are essential to mitigate further spread and impact. The Agency, through the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, has pioneered advanced fit-for-purpose diagnostics assays using the DNA endonuclease-targeted CRISPR trans reporter system. These highly sensitive assays are suitable for point-of-care diagnostic applications, supporting early intervention at primary points of entry while offering sustainable and cost-effective management. This technology is rapid, reliable and resource-efficient, requiring no sophisticated laboratory setup, minimal sample preparation and limited operator training.

Ionizing radiation can alter the physical, chemical and biological properties of materials, making it an essential tool in industry, medicine and scientific research. Irradiation facilities in Member States play a significant role in supporting Agency initiatives such as NUTEC Plastics and Atoms4Food. The Agency is bridging gaps in the knowledge and regulatory frameworks for electron beam technology through a strategic approach aimed at providing cost-effective and accessible equipment to Member States.

Non-destructive testing (NDT) is crucial for inspecting and evaluating additive manufacturing parts without causing damage. Unlike destructive testing, which requires the cutting or breaking of parts to analyse their properties, NDT techniques — including X-ray or gamma computed tomography, ultrasonic testing and laser-based methods — can assess parts for defects such as voids, cracks and lack of fusion.

Radioligand therapy (RLT) is a highly effective method of cancer treatment, particularly in advanced or metastatic stages where conventional therapies are less effective. Ongoing collaboration among researchers specializing in radionuclide production, radiochemistry, radiolabelling and chelator development — alongside preclinical and clinical evaluation — is pivotal in advancing clinically relevant radiopharmaceuticals for Auger electron-based RLT. The Agency plays a crucial role in facilitating these efforts, providing a platform for technical meetings and coordinated research projects aimed at advancing the next generation of RLT treatments.

Materials derived from renewable biological sources, also known as biomass, have garnered significant interest due to growing concerns over fossil fuel depletion and the environmental impact of petroleum-derived plastics. As consumers become more environmentally conscious, demand for sustainable products is rising. The use of ionizing radiation in producing bioplastics and the integration of biobased materials into high-value products are growing, alongside increased emphasis on enhancing regulatory frameworks and safety standards.

Effective groundwater management in the context of water scarcity and pollution in fast-recharging systems requires innovative approaches to monitor rapid water transfers between surface and groundwater systems. This knowledge is crucial for assessing the safety of water sources, particularly in emergency settings such as refugee settlements.

Global concern is rising over the impacts of ocean acidification on socioeconomically important seafood. Ocean acidification has become an integral part of the United Nations 2030 Agenda for Sustainable Development. The Agency is working to better understand marine environmental processes and pollution using non-traditional isotopes such as zinc, chromium, nickel and copper. These isotopes are gaining prominence in marine research, particularly in areas such as risk assessment, pollution monitoring and source identification. They help scientists understand how contaminants move through ecosystems.

A.

Nuclear Power

A.
Nuclear Power

A.1.
Nuclear Power Projections

Status

The 28th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28), held in Dubai, United Arab Emirates (UAE) in 2023, was historic in many ways, with a consensus on transitioning away from fossil fuels, tripling renewable energy capacity and doubling energy efficiency by 2030, and accelerating the deployment of all other low carbon technologies — including nuclear power, which was mentioned explicitly in the first Global Stocktake, marking the first time nuclear had been included in a COP negotiated outcome. This momentum was boosted at the 29th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP29), held in Baku, Azerbaijan in November 2024, where the indispensable role of nuclear energy in addressing climate change and facilitating the clean energy transition was continuously highlighted by the impactful engagement of the Agency in cooperation with the COP 29 Presidency and international partners, including more than 40 nuclear events at the Atoms4Climate pavilion and many other pavilions, to ensure that nuclear power and technologies remained at the forefront of the global dialogue on clean energy transitions.

IAEA projections for global nuclear capacity for electricity generation:

950 GW(e) High case projection

514 GW(e) Low case projection

For the fourth consecutive year, the Agency has revised upwards its annual projections for installed nuclear power capacity in the coming decades, reflecting the momentum behind its inclusion in the Global Stocktake concluded at COP28 and the pledge by 31 countries to triple global nuclear capacity by 2050, and the holding of the first-ever Nuclear Energy Summit in Brussels in March 2024. In its new outlook for global nuclear capacity for electricity generation, the Agency has increased its high case projection to 950 gigawatts GW(e) by 2050, representing 2.5 times the current installed capacity. The realization of this projection would

FIG. A.1. IAEA Director General Rafael Mariano Grossi at COP29 in Baku, Azerbaijan. 12 November 2024. (Source: IAEA) require large-scale implementation of long-term operation (LTO) across the existing fleet and about 640 GW of new build capacity in the coming three decades. Small modular reactors (SMRs) could represent nearly a quarter of that new build capacity. Enabling factors for such an expansion are the capability of industry to deliver on time and to budget, access to financing and a level playing field in terms of policies and incentives for all low carbon technologies, and an acceleration of the demonstration of SMRs. In the low case projection, installed nuclear capacity would increase to 514 GW by 2050 and SMRs would represent 6% of all added capacity.

Trends

The demand for clean energy continues to increase. The accelerating development of Artificial Intelligence (AI) applications that require power-consuming data centres contribute to this trend. This situation strengthens the considerable and growing interest in advanced and innovative reactor technologies, including SMRs, as source of clean and reliable electricity. The unique features of SMRs make them suitable not only for cogeneration and industrial applications but also for substitution of similarly-sized coal-fired power plants and for their usage in transport. These factors increase the attractiveness of SMRs, which are expected to constitute up to 150 GW of the new build addition calculated as 950 GW according to the IAEA high case projection.

The nuclear sector will continue to address a number of challenges — including access to financing, cost reduction, 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 Member States' efforts in this area, the Nuclear Harmonization and Standardization Initiative (NHSI), which was launched in 2022 to facilitate the global deployment of safe and secure advanced reactors with a focus on SMR technology, delivered its expected outcomes and is entering a second phase covering the period 2025–2026.

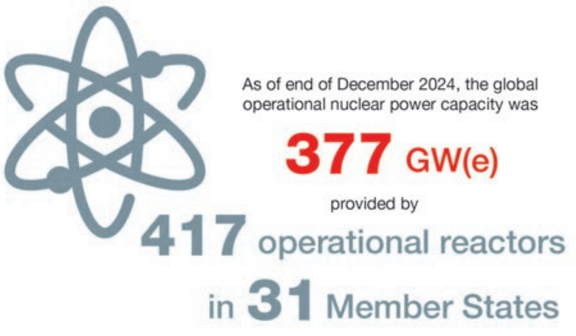
At the same time, some countries that had decided on early nuclear phase-out are reconsidering this option and engaging in unplanned LTO, sometimes with the encouragement of large industrial actors (such as data centres). 2024 also saw initiatives in the United States of America (USA) to restart the Palisades and Three Mile Island Unit 1 reactors, both having been shut down for economic reasons.

FIG. A.2. IAEA Director General Rafael Mariano Grossi at the Nuclear Energy Summit: Powering Tomorrow, Today; Brussels, 21 March 2024. (Source: IAEA)

A.2. Operating Power Plants

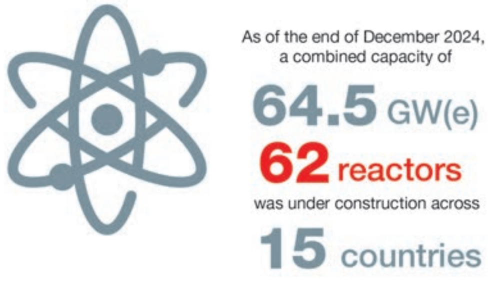
Status

As of the end of December 2024, global operational nuclear power capacity was 377 GW(e), provided by 417 reactors across 31 Member States. In addition, 23 reactors licensed for operation and representing capacity of 19.7 GW(e) were in suspended operation during 2024, this includes 4 reactors in India with a total net capacity of 639 MW(e) and 19 reactors in Japan with a total net capacity of 20 633 MW(e).



Total production of 2617.5 TW·h was reported in 2024, a 2.6% increase from 2023. The top three producers were the USA, which has the biggest fleet in the world and accounted for 30% (781.9 TW·h) of total reported nuclear electricity production, followed by China, which accounted for 16% (417.5 TW·h) and France, which has the highest share of nuclear in its electricity mix in the world (67.3%) and accounted for 14% (364.4.7 TW·h).

In 2024, four pressurized water reactors (PWRs) and one pressurized heavy water reactor (PHWR) with a total capacity of 5.7 GW(e) were connected to the grid in five different Member States. The UAE completed construction of a nuclear power plant (NPP), with Barakah Unit 4 (1310 MW(e)) connecting to the grid on 23 March 2024 and starting commercial operations on 5 September 2024. In China, Fangchenggang-4, the 1000 MW(e) HPR1000 reactor, was connected to the grid on 9 April 2024 and started commercial operations on 25 May 2024. In India, Kakrapar Unit 4, a 630 MW(e) reactor with domestic PHWR technology based on CANDU designs, was connected to the grid on 20 February 2024 and began commercial operations on 31 March 2024. In the USA, the Vogtle-4 AP1000 reactor (1117 MW(e)) was connected to the grid on 6 March 2024 and started commercial operations on 29 April 2024. In France, the Flamanville Unit 3 EPR (1630 MW(e)) was connected to the grid on 21 December 2024.



As of the end of December 2024, a combined capacity of 64.5 GW(e) (62 reactors) was under construction across 15 countries. Notably, China accounted for 46% of this global nuclear power expansion. During the year, construction

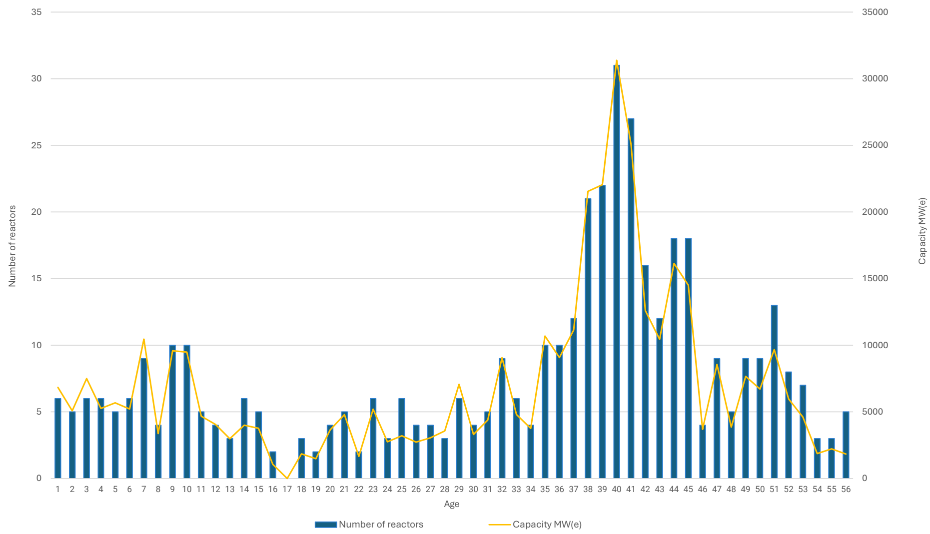


FIG. A.3. Age distribution of net operational capacity. (Source: IAEA Power Reactor Information System (PRIS))

began on nine PWRs in China, Egypt, Pakistan and the Russian Federation, with total capacity of 10.2GW(e). China began construction on six new reactor units with a total capacity of 6.8 GW(e). This includes four HPR1000 reactors — Ningde-5 (1200 MW(e)), Shidaowan-1 (1134 MW(e)), and Units 3 and 4 at Zhangzhou site (1129 MW(e) each) — and two CAP1000 units, Lianjiang-2 (1224 MW(e)) and Xudabu-2 (1000 MW(e)). In Egypt, construction of the 1100 MW(e) El Dabaa-4 VVER-1200 reactor began on 23 January 2024. On 30 December, Pakistan started construction of the 1117 MW(e) Chasnupp-5 reactor, a Hualong One unit developed in partnership with China National Nuclear Corporation. Meanwhile, the Russian Federation commenced construction of Leningrad 2-3 (VVER, 115 MW(e)) on 14 March 2024, aiming for operational start-up by end of January 2031.

Approximately 66% of global operational reactor capacity (296 reactors, 263.3 GW(e) — have been in operation for over 30 years, of these, approximately 34% (166 reactors, 135.5 GW(e)) of the total installed capacity — have been in operation for over 40 years. The ageing fleet highlights the need for new or uprated operating nuclear capacity to offset planned retirements and continue contribution to sustainability, global energy security and the achievement of climate change objectives. Governments, utilities and other stakeholders are investing in LTO and ageing management programmes for an increasing number of reactors so as to ensure sustainable operation and a 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 load factor was 87.74%. Boiling water reactors (BWR) and PWRs have been the best performing reactors since 2013, with median load factors of 89.3% and 82.7% respectively.

During 2024, 2.9 GW(e) of nuclear capacity (4 reactors) were permanently taken offline. In the Russian Federation, Kursk-2 (925 MW(e)), a light water cooled, graphite moderated reactor (LWGR), was shut down on 31 January 2024 after 45 years of operation. In Taiwan, China, the Maanshan-1 PWR (936 MW(e)) was retired on 28 July 2024 after 40 years of service. In Canada, Pickering, units 1 and 4, both pressurized heavy water reactors (PHWR), were retired on 1 October and 31 December respectively.

Trends

At the end of 2024, the 70 years of worldwide cumulative operating experience amounted to over 20166 reactor-years, provided by 653 reactors with a total capacity of 504.7 GW(e) across 35 countries. Nuclear power capacity has remained at a consistent level over the past decade, ranging between 353.9 GW(e) in 2014 and 377 GW(e) in 2024. About 72.5 GW(e) was connected to the grid since the beginning of 2014. While the global nuclear operating capacity has remained stable over the past decade, nuclear electricity production has generally increased, with a notable 5.3% rise over the past two years—from 2486.8 TWh in 2022 to 2617.5 TWh in 2024.

Over the past decade, 72.5 GW(e) (72 reactors) of net capacity have been connected to the grid, with 76% (54.3 GW(e), 51 reactors) coming from Asia. China has driven the region's growth, adding 39.0 GW(e) (38 reactors) to the grid since 2014.

A.3. New or Expanding Nuclear Power Programmes

Status

Some 50 countries have an interest in adding nuclear power to their energy mix to support national socioeconomic development. Of these, 37 countries are in various phases of initiating or implementing their national nuclear power programmes.

Twenty three countries are in the decision-making phase — that is, they are considering nuclear power without having made a decision (Algeria, Azerbaijan, El Salvador, Ethiopia, Indonesia, Iraq, Jamaica, Malaysia, Mongolia, Morocco, Myanmar, Niger, Norway, Rwanda, Senegal, Serbia, Singapore, 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 and the needs and requirements for a successful nuclear power programme. Others have initiated their programmes and are working on establishing national coordination mechanisms and developing road maps.

Fourteen countries are in the post-decision-making phase — that is, they have decided to introduce nuclear power and are building the necessary infrastructure or have signed a contract and have started or will soon start construction. The Philippines moved from the decision making phase to the post decision making phase, while Viet Nam decided to re-start its nuclear power programme and invited an Integrated Nuclear Infrastructure Review (INIR) Phase 2 mission to be conducted in 2025.

At the Bangladesh’s Rooppur NPP and Türkiye’s Akkuyu NPP, the construction of the first units (both VVER 1200) is nearing completion and fuel loading and test operations are expected to be performed in mid-2025, with planned commercial

FIG. A.4. IAEA Director General Rafael Mariano Grossi meeting HRH Prince Abdulaziz bin Salman Al-Saud, Minister of Energy of the Kingdom of Saudi Arabia, during a bilateral meeting at the 68th regular session of the General Conference. (Source: IAEA)

FIG. A.5. INIR Phase 2 mission in Poland, 14 April 2024. (Source: Ministry of Climate and Environment)

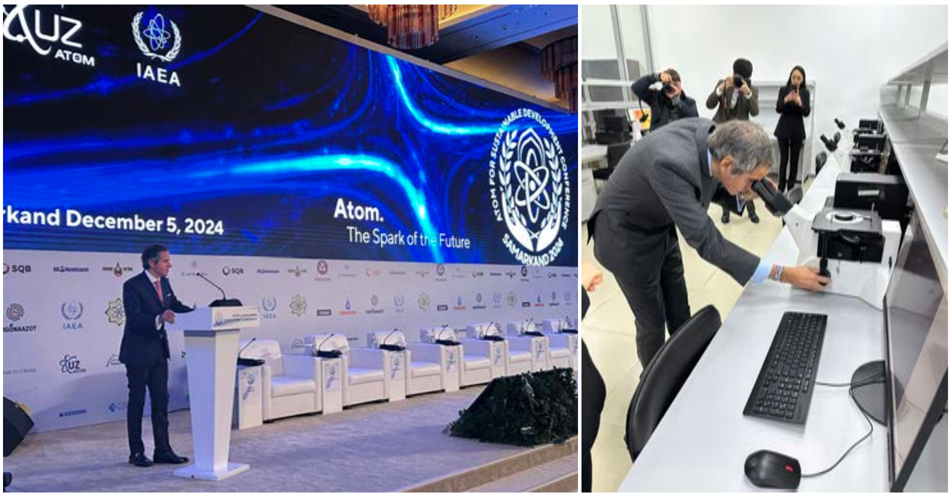


FIG. A.6. IAEA Director General Rafael Mariano Grossi at the Conference on Perspective use of Nuclear Energy for Peaceful Purposes in Sustainable Development of Organization of Islamic Cooperation Member States: International and National Experience, Samarkand, Uzbekistan, 5 December 2024. (Source: IAEA) (left); and IAEA Director General Rafael Mariano Grossi visiting the Tashkent branch of the National Research Nuclear University MEPhI, which is engaged in nuclear education. (right).

operations following the completion of all commissioning and testing. The first concrete for Egypt's El-Dabaa Unit 4 (VVER-1200) was poured in January 2024 and construction of the inner containments for Units 1 and 2 started in March and September 2024 respectively. In Saudi Arabia, the NPP technology vendor selection process is expected to be completed in 2025, with the first unit to be commissioned in 2036.

In Poland, the technology and vendor selection process for the construction of PWRs with a total installed nuclear power capacity of 6000–9000 MW(e) by 2042 was completed. Several contracts have been signed and work is ongoing on the final engineering, procurement and construction (EPC) contract for the first NPP, which will include three AP1000 reactors. Poland hosted an INIR Phase

FIG. A.7. Interregional Workshop on Self-Evaluation of Infrastructure Development for Nuclear Power Programmes, Jakarta, Indonesia, 23-27 September 2024. (Source: Indonesia National Research and Innovation Agency)

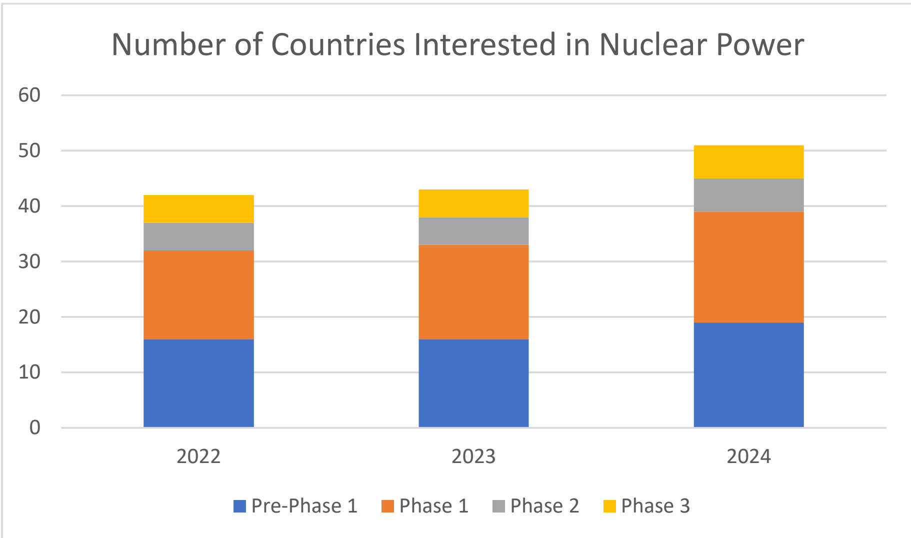


FIG. A.8. Number of countries in different phases of the Milestones approach. (Source: IAEA)

2 Mission in April 2024 to evaluate the status of infrastructure development to support the contracting and construction stages.

An INIR Follow-up Mission to the Philippines was conducted from 2 to 6 December 2024 to assess the progress made in addressing the recommendations and suggestions made during the main INIR mission in 2018 to assist the Philippines in its infrastructure development. A presidential executive order in 2022 outlined the Government's position on the inclusion of nuclear energy in the country’s energy mix. In 2024, the Philippines announced its Nuclear Energy Roadmap aiming to ensure that there are commercially operational nuclear power plants by 2032, with at least 1200 MW initially and increasing gradually to 4800 MW by 2050.

Jordan continued finalizing a bid invitation specification for an SMR project for electricity production and seawater desalination, with an aim to issue in 2026. Ghana expanded its choice of reactor technology to include SMRs and is currently reviewing proposals from five potential vendors for the development of around 1000 MW(e), with commissioning planned for 2029. Kenya continued preparing bidding documents for the construction of both SMRs and large NPPs. In Uzbekistan, a contract to build six 55 MW(e) RITM-200N reactors with a total capacity of 330 MW(e) was signed in May 2024.

Estonia is only considering SMR technology for its nuclear power programme. An INIR Phase 1 mission conducted in October 2023 helped the country to finalize the comprehensive assessment of its nuclear power infrastructure. The result of this assessment was submitted to the Government, and in June 2024 the Estonian Parliament passed a resolution supporting the introduction of nuclear power in the country.

Kazakhstan selected a site for the construction of its first NPP and continued to develop a bidding and contracting strategy and related documents. In a nationwide referendum on the introduction of nuclear power in Kazakhstan, 71% of voters supported nuclear power. Kazakhstan is also considering SMRs.

The Agency continued to support nuclear power infrastructure development through national, regional and interregional activities.

Trends

An increasing number of countries are considering nuclear power to support socioeconomic development and to address issues relating to energy security and climate change. In 2024, five countries were added to the list of countries working on pre-feasibility studies to support decision making for the introduction of nuclear power. In addition to the 32 countries that are working on pre-feasibility studies or developing infrastructure and constructing their first NPPs, some 20 other countries are interested in nuclear power and are looking into its inclusion in their future energy mix. The Agency has developed a new approach to ensure

FIG. A.9. Director General Rafael Mariano Grossi speaks with members of the World Bank Group Executive Board in Washington on 27 June 2024. (Source: IAEA) early engagement with these countries, to help them establish coordination mechanisms and an initial roadmap for the way forward and to initiate the necessary pre-feasibility studies to support decision making. In this context, countries' infrastructure preparedness needs to be stepped up, with Agency support, to ensure responsible deployment.

Decision making and the implementation of projects to build new NPPs is also progressing in many expanding countries such as Argentina, Armenia, the Czech Republic, Hungary, the Islamic Republic of Iran, Pakistan, Romania and Slovakia. Some other countries are also considering expanding their existing nuclear power programmes. The nuclear industry in several Member States is supporting the renewed interest in nuclear energy worldwide and is developing additional capacities to produce new components. A number of countries have included SMRs in their technology considerations and continue to monitor related developments. Interest is driven by advances in SMR technology and the 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 nuclear power programmes based on evolutionary NPPs continue to show an interest in large-scale NPP technologies.

A.4. Nuclear Power Technology Development

Status

The COP28 pledge, made by more than 30 countries by the end of 2024, aims to triple operational nuclear capacity by 2050. With the growing interest in expanding or preparing for the first use of nuclear power, an urgent acceleration of the deployment of advanced NPPs is required. The immediate emphasis remains on the deployment of advanced large NPPs for electricity generation based on established and demonstrated technology, almost exclusively represented by advanced water-cooled reactor technologies. At the same time, the interest in SMRs and a number of different evolutionary and innovative technologies is growing and is, furthermore, associated with many other applications beyond power generation, and a more sustainable future. To decarbonize the energy sector beyond electrification, in particular in relation to energy-intensive industrial activities, the full use of available heat is pursued through cogeneration and non-electric applications such as the delivery of process steam, hydrogen production, district heating and desalination. The higher operating temperatures of advanced reactor technologies, such as high temperature reactors, molten salt reactors and fast spectrum liquid metal and salt cooled designs, are therefore particularly attractive, although a huge proportion of the heat demand can be met by existing and near-term deployable solutions, since only modest temperatures (below 500oC) are required. The further exploration of innovative applications — including maritime use for cogeneration and propulsion, space applications and microreactors for off-grid areas — continues to grow.

The 33rd INPRO Steering Committee Meeting, attended by 46 IAEA Member States and the European Union, held in October 2024, endorsed the INPRO Strategic Plan 2024-2029 and the implementation of the new collaborative project entitled "Building Capacity in Strategic Planning for Sustainable Nuclear Energy Through Educational Programmes" (in implementation of INPRO's model curriculum).

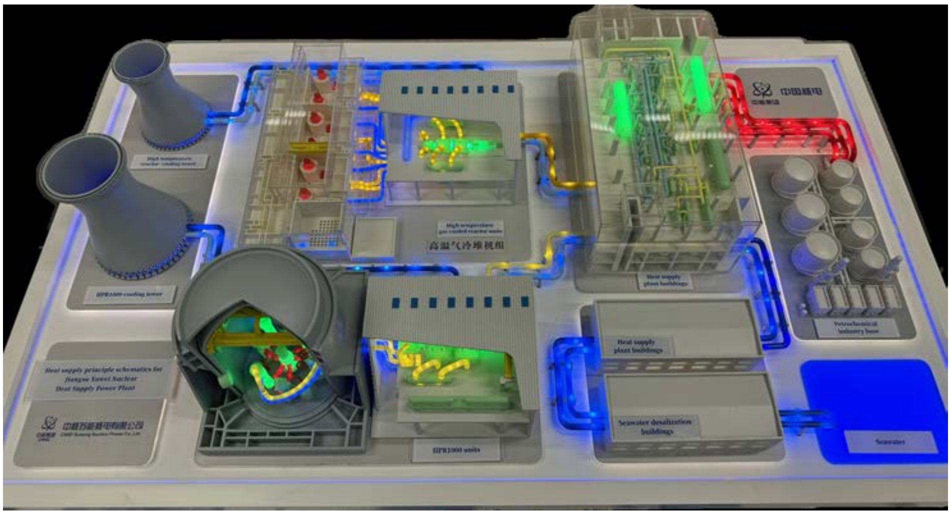


FIG. A.10. Model of the phase 1 Jiangsu Xuwei nuclear power heating plant project, with two HPR1000 reactors (one unit shown in foreground) and one HTR-PM600S (six reactors shown in the centre), as presented to the Agency. (Source: IAEA)

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 considered worldwide for a range of applications. The current trend in SMR development focuses on improving their economics, safety features and scalability.

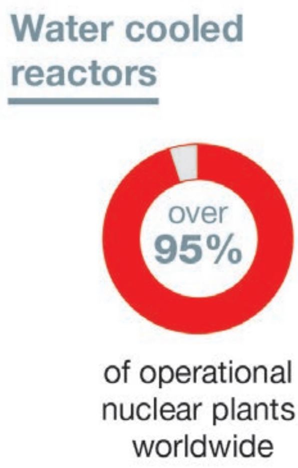
Current trends in fast reactor technology development focus on improving safety measures by incorporating passive shutdown systems and exploring different coolants, particularly in the context of innovative reactor designs. There is also a strong emphasis on improving the economics of fast reactors to reduce construction costs and to improve the potential of fast reactors to significantly reduce the radiotoxicity of final high level waste subject to final disposal. It should also be noted that the developers and operators of fast neutron reactors are striving to find an optimal place for them in the nuclear fuel cycle based on the advantages of these reactors, including the simplified requirements for the isotopic composition of plutonium, the ability to transmute minor actinides and the possibility of producing plutonium.

In an important step towards decarbonizing industry, a first major project dedicated to heating and power was announced in 2024. Two HPR1000 LWRs and the HTR-PM600S, comprising six high temperature gas cooled reactor (HTGR) modules, will supply over 4000 t/h of high-quality steam (up to 460oC) and up to 1653 MW(e) to the Lianyungang petrochemical park in Jiangsu, China, by 2030.

A.4.1. Advanced Water Cooled Reactors

Status

Water cooled reactors (WCR) continue to dominate the commercial nuclear power industry, powering over 95% of operational nuclear plants worldwide. Recent milestones in WCR technology reflect a global commitment to innovation, with a strong emphasis on safety, efficiency and sustainability. Key features of advanced WCRs include passive safety systems that require minimal operator intervention, advanced fuel technologies for higher resilience, improved cooling methods and strategies for efficient waste management. In 2024, the global focus on enhancing WCR performance intensified, driven by demands for reliable energy and climate resilience. Significant developments in materials science and computational modelling are further enhancing reactor efficiency and safety. Key advancements in advanced WCR design include new operational reactors, like the AP1000 in the USA, the APR1400 in the UAE, the HPR1000 in China and the EPR1650 in France, showcasing passive safety innovations. The Russian Federation's work on the VVER-S reactor and global R&D on supercritical WCRs demonstrate the shift towards modular, adaptable systems. The Russian Federation is also working on the VVER-1200 and VVER-TOI projects. National studies on hybrid nuclear–renewable energy applications are exploring ways to leverage WCRs for grid stability and non-electric applications, thus supporting a sustainable energy future.



Trends

There are 58 WCR units under construction in 14 Member States, of which 55 are advanced PWRs (ACP100 (1), APR-1400 (2), CAP1000 (8), CAREM (1), EPR (2), HPR1000 (14), Pre-Konvoi (1) and VVER (25)), 2 are advanced BWRs and 1 is a PHWR.

Advanced WCRs are valued for their reliability and safety and increasingly incorporate passive safety systems to enhance resilience against severe accidents without needing external power, aligning with global safety standards.

Many countries are extending the life of existing reactors by modernizing key components, thereby maximizing the output of established infrastructure. Additionally, modular construction techniques are becoming more prevalent, allowing for faster and more cost-effective deployment.

Globally, new WCRs are often co-located with existing units, particularly in nuclear markets across Asia and Africa, where demand for reliable, large-scale power sources is growing. The next few years in advanced WCR development will focus on enhancing safety, flexibility and sustainability. As WCRs adapt to evolving energy systems and climate priorities, they will play a crucial role in achieving reliable, low carbon energy solutions on a global scale.

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

Status

SMRs, including microreactors, are expected to play an important role in nuclear power expansion as part of global ambitions to reach net zero carbon emissions. SMRs are primarily based on the major technology types (as shown in the figure above) and well positioned to enable the decarbonization of electricity and industries. Their power range of up to 300 MW(e) per unit make them well suited to replace ageing fossil-fuelled power plants and to supply power for small electrical grids and remote regions. SMRs are also expected to support flexible power supply in synergy with renewables and energy storage systems and to offer non-electric applications, including nuclear desalination and hydrogen production. As a first step towards achieving this goal, an SMR using high temperature gas cooled reactor technology, called the High Temperature Reactor–Pebble-Bed Module (HTR-PM), started commercial operation in China in December 2023, supplying 200 MW(e) from two modules to the grid, as well as district heating. With a high degree of modularity and standardization incorporated in their design, SMRs are aimed at achieving a shorter construction schedule and lower upfront capital costs, thus facilitating project financing. SMRs offer a new nuclear power technology option for grids and industrial applications for which large nuclear power reactors would not be viable. In the past decade, SMRs have also emerged as the preferred technology for marine-based NPPs, including transportable floating power units, as well as a platform of power supply for the oil and gas industries. The shipping industry has also declared an interest in the technology as a potential solution for it to reach net zero carbon emissions by 2050.

The Agency's first International Conference on Small Modular Reactors and their Applications was held in October 2024. Opened by the Director General, the Conference attracted more than 1200 participants from 97 Member States and 18 international organizations.

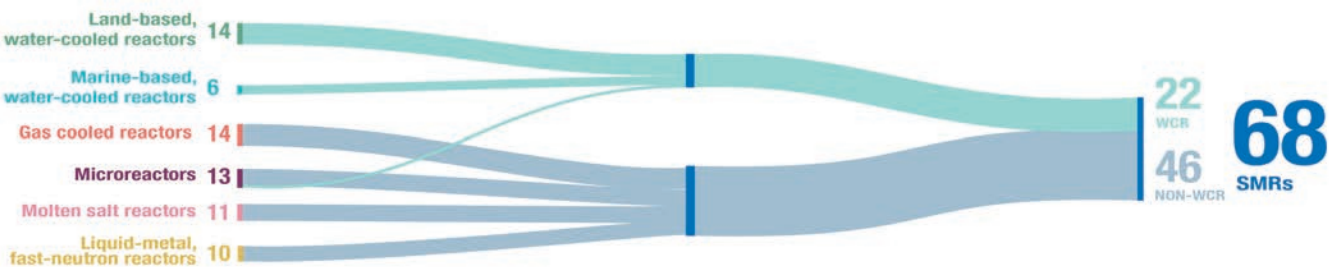


FIG. A.11. Breakdown of the 68 active designs in the Agency publication Small Modular Reactors: Advances in SMR Developments 2024. (Source: IAEA)

Trends

Overall interest in SMRs continues to grow, with an increasing number of Member States also considering SMRs for the first deployment of nuclear power. Throughout 2024, Member States' interest in floating NPPs and microreactors, as well as their applications, also increased. Significant industrial and regulatory efforts are ongoing to facilitate their design, development and early deployment. Technology with a higher degree of maturity or readiness level has prospects for early deployment around 2030. In 2024, technology development activities for microreactors as a subset of SMRs continued in Canada, the Czech Republic, France, Japan, the Russian Federation, South Africa and the USA. Existing microreactor designs are to generate power in the lower range, up to 20 MW(e), offering an optimal solution for future niche electricity and district heating markets for communities, mines and fisheries in remote regions with no access to the grid, which for decades have been served by diesel power plants. Gas cooled reactors, liquid metal cooled reactors with a fast neutron spectrum, and heat pipes are among the technologies adopted for microreactors.

An increasing number of countries are engaged in the design development of marine-based SMRs for floating NPPs, for onshore and offshore applications. The first floating NPP with SMRs based on the KLT-40S design has started its second four-year cycle since going into commercial operation in the Russian Federation in 2020. A start-up company in Denmark is developing a 100 MW(e) compact molten salt reactor for a floating NPP. The Republic of Korea is continuing the development of the BANDI-60, a compact PWR to generate 60 MW(e). The Russian Federation has adopted the RITM-200M design for future floating NPPs. China is also developing the ACP100S (a variant of the ACP100 land-base design under construction).

FIG. A.12. IAEA Director General Rafael Mariano Grossi; John Hopkins, NuScale Power; Ramzi Jammal, the Canadian Nuclear Safety Commission; Xavier Ursat, EDF; and Zhengyu Zou, China National Nuclear Corporation at the International Conference on Small Modular Reactors and their Applications, Vienna, Austria, 21 October 2024. (Source: IAEA)

These marine-based SMRs are intended for specific purposes, including distributed power generation and heat supply to remote communities, the shipbuilding industry and desalination, and as a complement to hybrid energy systems with a higher share of renewables. The legal, regulatory and institutional aspects of these transportable SMR projects are being assessed to facilitate deployment.

Many SMR designs are based on integral PWR and natural circulation BWR technologies as they benefit from their similarities to existing commercial large LWR designs. Two integral PWR designs are under construction for connection to the grid by 2030.

In this fast-developing scenario, the IAEA Platform on Small Modular Reactors and their Applications (SMR Platform), established in 2021 by the Director General, coordinates the Agency's activities in the field of SMRs. In 2024, the SMR Platform continued to coordinate Agency efforts to strengthen support to Member States and other stakeholders interested in the early deployment of SMRs. The SMR Platform is supported by 17 different sections throughout the Agency.

STRUCTURE

The SMR Platform Steering Committee (SMR-SC) is the senior governing body chaired by the IAEA Deputy Director General and Head of the Department of Nuclear Energy. It comprises Directors from relevant departments and offices reporting to the Director General.

The SMR Platform Implementation Team (SMR-PIT) comprises Heads of Sections from relevant IAEA departments and offices reporting to the Director General, and Task Forces which are organized thematically to address specific requests from Member States and other stakeholders.

The Nuclear Harmonization and Standardization Initiative (NHSI) is aimed at facilitating the effective global deployment of safe and secure advanced nuclear reactors. It is implemented under the guidance of the IAEA Director General and the supervision of the Deputy Directors General, Heads of the Department of Nuclear Energy and of the Department of Nuclear Safety and Security. It is comprised of two separate but complementary tracks:

- **NHSI Industry Track** chaired by the Director of the Division of Nuclear Power, is focused on four topics: harmonization of high-level user requirements, common approaches on codes and standards, experimental testing and validation of design and safety analysis computer codes for SMRs and accelerating the implementation of nuclear infrastructure for SMRs.
- **NHSI Regulatory Track** chaired by the Director of the Division of Nuclear Installation Safety, is comprised of three working groups: building an information sharing framework, development of a multi-national pre-licensing regulatory design review, and development of approaches to leverage other regulator's reviews and supporting regulators undertaking collaborative reviews.

A NHSI Special Task Force, co-chaired by both Directors, has been established under the IAEA SMR Platform to ensure coordination with the Agency's activities in the area of SMRs.

The SMR Portal (https://smr.iaea.org) provides Member States and other stakeholders with a comprehensive and systematic overview of all the Agency's services and activities on SMRs and their Applications. The Portal serves as tool for sharing information with external stakeholders and as an entry point for Member States and other stakeholders to request assistance. Requests for assistance or additional information can be made by contacting SMR.Platform@iaea.org

A.4.3. Fast Reactors

Status

As of December 2024, the Russian Federation operated three sodium cooled fast reactors (SFRs), including one experimental 60 MW(e) BOR-60 and two large-sized fast reactors, BN-600 and BN-800, with installed capacity of 600 MW(e) and 880 MW(e) respectively. In China, in addition to the 20 MW(e) China Experimental Fast Reactor (CEFR) which has been in operation since 2010, construction is under way on two identical CFR-600 units — 600 MW(e) industrial power SFRs. The first unit is currently under commissioning and the second is expected to start operations in 2028. In India, the Prototype Fast Breeder Reactor (PFBR), an experimental industrial sized SFR with a capacity of 500 MW(e), is currently under commissioning with first criticality expected in 2025-2026. In addition to sodium cooled reactors, which have a long development history, several novel fast neutron systems are attracting significant interest. Of the six innovative reactor concepts promoted by the Generation IV International Forum, three are fast neutron reactors and another two rely on a mixed (including fast) neutron spectrum. One promising innovative technology, the heavy liquid metal cooled reactor, is under intensive development in several countries, with the Russian Federation building a 300 MW(e) demonstration lead cooled fast reactor (LFR), the BREST-OD-300.

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-1200M reactor and constructing the 150MW(t) Multipurpose Fast Research Reactor (MBIR). China is extending its SFR projects through the development of a 1000 MW(e) CFR-1000 Generation IV reactor. TerraPower, a company based in the USA, has started

FIG. A.13. Construction status of BREST-OD-300 lead cooled fast reactor in Seversk, near Tomsk, Russian Federation, April 2024 (Source: Siberian Chemical Plant) construction of the Natrium SFR, which operates in connection with a molten salt storage system. The Natrium reactor is designed to reach a peak power of 500 MW(e) and can be integrated with other energy sources. Another US SFR project, the Versatile Test Reactor, has been awaiting US Congress approval since 2021. In France, among the 11 projects selected in the 'France 2030' first call for innovative nuclear projects, six EU companies were selected for the development of fast neutron SMRs with three projects based on liquid metal technologies and three projects on molten salt technologies, alongside other projects based on PWR, HTR, and fusion by magnetic or inertial confinement technologies.

While SFRs remain the most mature technology, several countries are constructing and developing LFRs, such as the BREST-OD-300, which is currently under construction in the Russian Federation and is expected to be commissioned in 2028. In the Russian Federation, the development of NPP with BR-1200M lead-cooled fast reactors is also underway as part of the creation of industrial energy complexes combining NPPs and closed nuclear fuel cycle enterprises on one site. Under current plans, 8 fast reactors of high capacity are expected to be built by 2042 in the Russian Federation. The joint Italy–Romania 120 MW(e) Advanced Lead Fast Reactor European Demonstrator and several SMR-type LFR designs in China and France are also being developed. Start-up companies are working on the development of the 55 MW(e) Swedish Advanced Lead Reactor (SEALER), the 30 MW(e) LFR-AS-30 in France and the 200 MW(e) LFR-AS-200 in the United Kingdom (UK), with R&D also under way in Italy. Other fast neutron spectrum reactor technologies, such as gas cooled fast reactors and molten salt fast reactors, are being developed in several Agency Member States.

A.4.4. Non-electric Applications of Nuclear Power

Status

Non-electric applications of nuclear energy have been implemented in several Member States for many years, and numerous other Member States are exploring this area to meet climate goals. Currently, 67 reactors can be used for non-electric applications such as industrial process heating, district heating and desalination. In 2024, out of the 67 reactors, 46 nuclear power reactors across 10 Member States supplied 2644.1 GWh of electrical equivalent of heat for non-electric applications. The majority of this heat (94%) was utilized for district heating, totalling 2487.4 GWh, in Bulgaria, the Czech Republic, China, Hungary, Russia, Romania, Slovakia and Switzerland. Industrial heating in India and Switzerland was supported by 107.4 GWh (4%) of electrical equivalent of heat, while 49.2 GWh (2%) was used for desalination in India and Japan.

Nuclear energy is uniquely suited to decarbonize many hard-to-abate sectors through the production of heat for various industrial processes. Many Member States and industries are investigating the potential of nuclear energy to fulfil the needs of oil refineries, cement factories, petrochemical plants and fertilizer plants, among other things. In 2024, China commissioned its first industrial nuclear steam supply project, with Tianwan NPP supplying 600 tonnes of steam per hour to a nearby petrochemical plant. The use of nuclear energy to supply industrial process heat has been demonstrated for many years at facilities such as Gösgen NPP in Switzerland, which has supplied steam for a cardboard factory and paper mill since 1979, and Rajasthan NPP in India, which has produced heavy water since 1980, mainly for on-site use. In France, several companies supported by the “France 2030” call for Innovative Nuclear Reactors projects aim to support the decarbonization of industry by providing lower carbon heat sources.

The use of nuclear energy to power data centres and AI is expanding rapidly to deal with the unprecedented growth in energy demand in these areas. Major technology companies are investing directly in nuclear to meet their increasing energy needs while reaching climate targets.

Many Member States are investigating the use of nuclear energy for hydrogen production, including Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation, Sweden, the UK and the USA. In the Republic of Korea, a demonstration project involving a 10 MW(e) low temperature electrolysis hydrogen production plant coupled to an NPP is planned, led by Korea Hydro & Nuclear Power and with the participation of 13 research institutions. In addition to low temperature and high temperature electrolysis, many countries — including Canada, China and India — are developing capabilities for thermochemical cycles to produce nuclear hydrogen. The UK is planning to install a solid oxide electrolyser at Heysham B nuclear power station to create clean hydrogen, using high temperature steam electrolysis, to be used to decarbonize asphalt and cement production. The consortium is made up of EDF, construction materials producer Hanson, the UK National Nuclear Laboratory and Vulcan Burners. In the Russian Federation, at the Kola Nuclear Power Plant, it is planned to build a test bench complex for hydrogen production, and a project for a nuclear power plant with a high-temperature gas-cooled reactor (HTGR) and a hydrogen production unit is being developed.

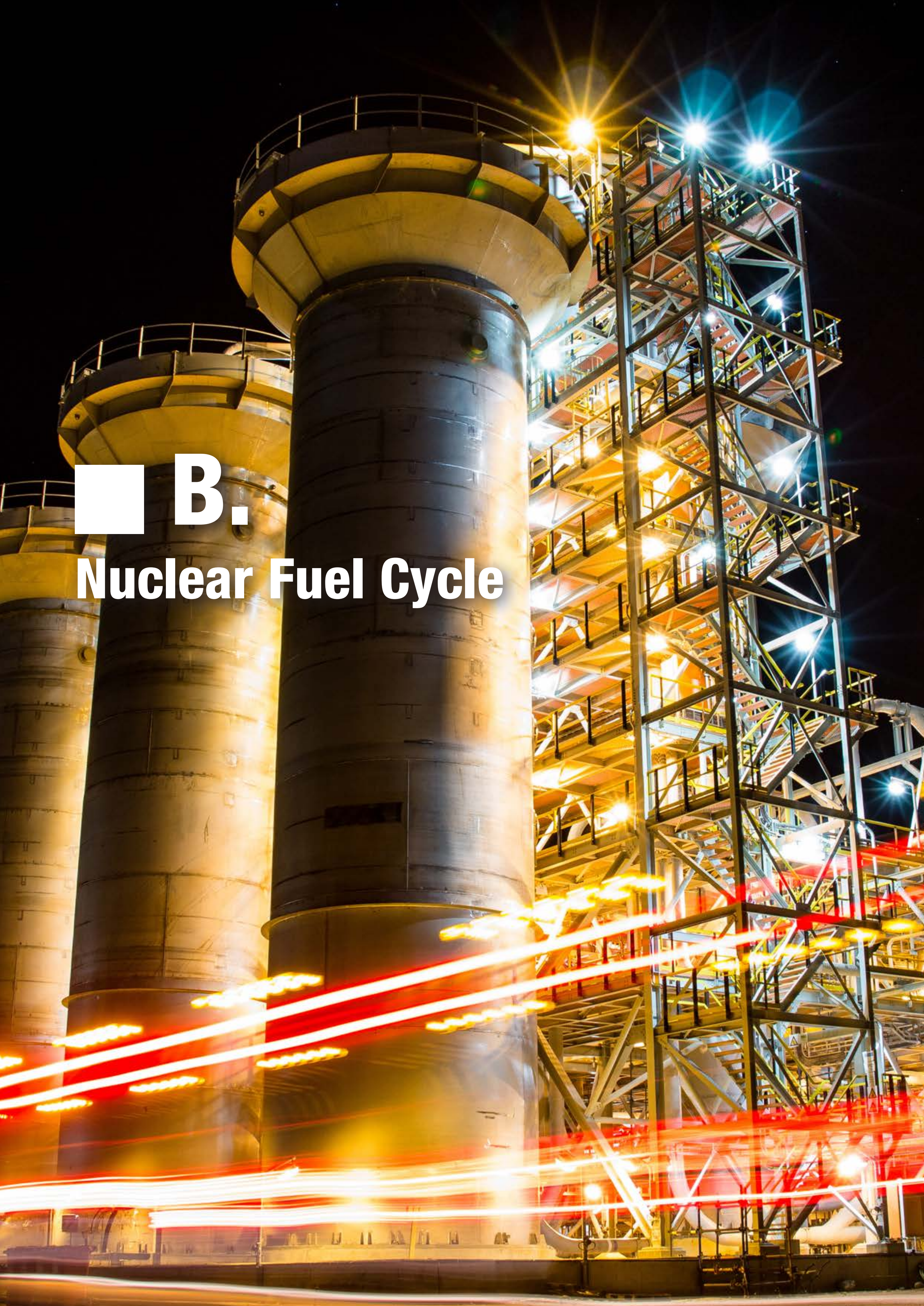
Additional non-electric applications such as district heating and desalination continue to be of interest to Member States. Three cities in Finland have signed agreements to evaluate the feasibility of deploying SMRs for district heating. In 2023, the Agency conducted an expert mission to Jordan on SMRs for electricity and potable water production.

FIG. A.14. High temperature electrolysis testing facilities at the Idaho National Laboratory. (Source: Idaho National Laboratory)

Trends

The unique combination of reliable, low carbon heat and electricity from nuclear energy continues to drive interest in non-electric applications. The implementation of these applications will assist in reaching carbon goals, by decarbonizing sectors such as heating, transportation and other industries that are currently powered by fossil fuels and generate a majority of greenhouse gas emissions worldwide. Additionally, nuclear energy can be used in space and marine applications, providing either thermal or electric propulsion. It can also support hybrid energy systems, where it can be coupled with other solutions such as renewable sources and energy storage to achieve cost savings and enhanced capabilities.

B.
Nuclear Fuel Cycle



B. Nuclear Fuel Cycle

B.1. Front End

Status

In January 2024, the uranium spot price hit a 17-year high of US $106/lb U3O8 (US $275/kg U), and since mid-2024, it has been fluctuating between US $80/lb U3O8 (US $208/kg U) and US $85/lb U3O8 (US $221/kg U). This is a dramatic increase (about 400%) from the relatively flat 2016–2021 market prices of around US $20–30/lb U3O8 (US $52–78/kg U).

The publication *Uranium 2024: Resources, Production and Demand*, also known as the 'Red Book' and jointly prepared by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) and the Agency, reported that global uranium mine production, after declining by 14% between 2019 and 2020 from 54 478 to 47 581 tonnes of uranium (tU), increased by 4% between 2021 and 2022 (47 361 to 49 490 tU) and is estimated to have increased by 9% in 2023 to 54 345 tU. During this period, major uranium producing countries, including Canada, Kazakhstan and Namibia, resumed operations that had been limited or curtailed by the global COVID-19 pandemic in 2020–2021.

Global identified recoverable conventional in-ground uranium resources (i.e., resources that are reasonably assured and inferred to exist in geological deposits that are typically mined) are adequate to support near- and mid-term growth in nuclear generating capacity. The Red Book 2024 reports over 10 million tonnes and around 7.9 million tonnes of identified in-ground uranium

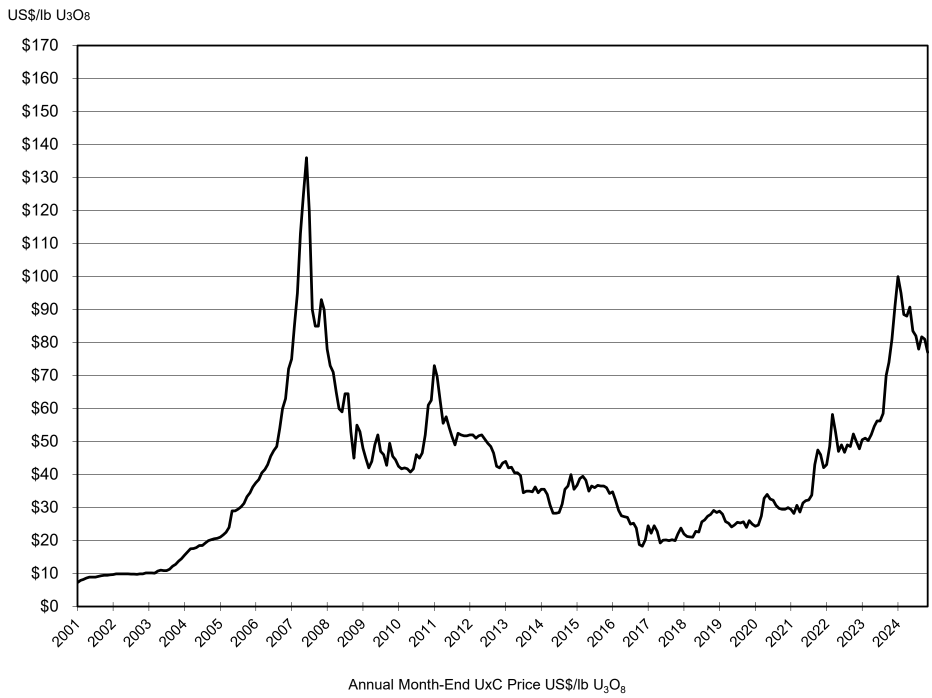


FIG. B.1. 2001–2024 annual month-end UxC uranium spot price. (Source: UxC, LLC)

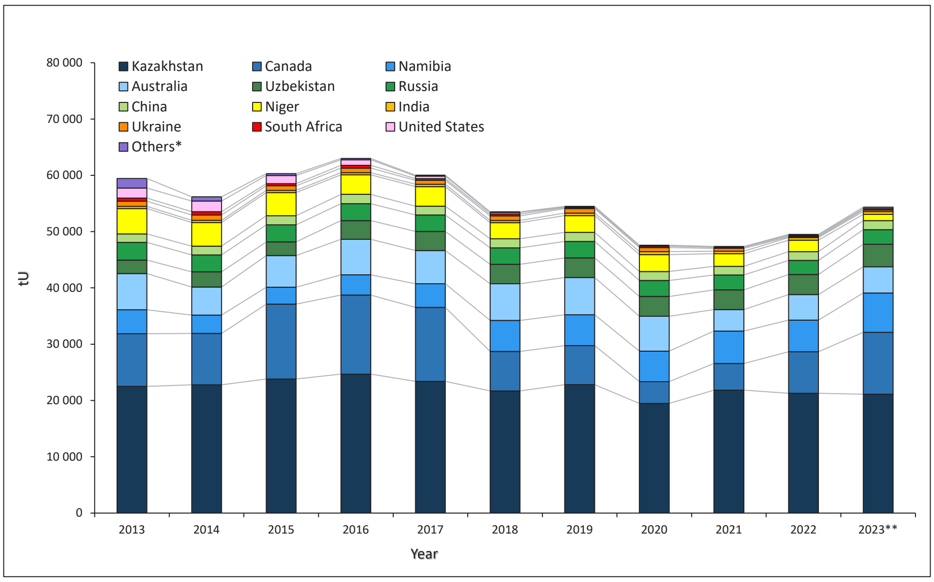


FIG. B.2. Past decade of global uranium production. (Source: IAEA)

** 'Others' includes the remaining small producers.*
*** NEA/IAEA estimate.*

resources that are recoverable, respectively for the <USD 260/kgU and for the <USD 130/kgU categories. Given the global reactor-related uranium requirements (59 018 tU in 2022), these resources are sufficient for more than 130 years, if they are all brought to production. However, this figure does not take into account the implications of the recent declaration made at COP28 to triple nuclear power capacity by 2050, nor of the envisioned widespread deployment of SMRs that could make up 25 % of the nuclear power fleet.

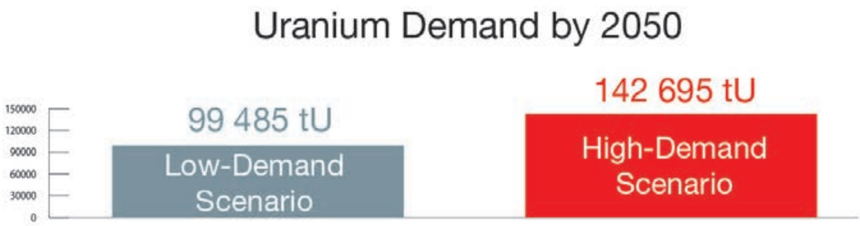
A nuclear fuel assembly is not a fungible commodity, but a complex product resulting from design, licensing and R&D activities that needs to meet certain specifications. These specifications are determined by the physical characteristics of the reactor, by the reactor operating and fuel cycle management strategy of the utility, and by national or regional licensing requirements. Nuclear fuel production is a mature technology that has developed over the years, with improvements made in the areas of automation, digitalization, reduced waste and enhanced radiation safety for workers. The global fabrication capacity for LWR fuel is about 15 000 tonnes of heavy metal (tHM) per year, while for PHWR fuel it exceeds 5300 tHM per year. Currently, these capacities are sufficient to meet anticipated demand.

Member States have made significant advancements in the areas of economic efficiency, reliability and sustainability, with extended R&D on innovative fuels such as accident tolerant or advanced technology fuels (ATFs) and fuels for advanced reactors, including SMRs. These may necessitate new fabrication facilities and careful licensing owing to higher enrichment levels, as in the case of LEU+ or high assay low enriched uranium (HALEU). The Agency's coordinated research project (CRP) 'Testing and Simulation for Advanced Technology and Accident Tolerant Fuels (ATF-TS)' supports Member States engaged in Research Development & Deployment programmes for the industrial implementation of innovative fuels, while the CRP 'Fuel Materials for Fast Reactors' involves Member States interested in the development of fast reactors, including SMRs.

Trends

During COP28, 22 countries made a declaration to advance the aspirational goal of tripling nuclear power capacity by 2050. Global forecasts from the Red Book 2024 indicate that, by 2050, uranium demand could range from 99 485 tU (low-demand scenario) to 142 695 tU (high-demand scenario).

Planned and prospective mines in 19 countries could, as they come online from 2025 through 2050, contribute to a global total nominal production capacity of 80 494 tU annually. The assurance of uranium supply will require that idled mines come back online and that planned and prospective mine projects be realized, and the discovery of new deposits will require that the current favourable market conditions be sustained. 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 the start of mining operations. Also, significant and timely investment in exploration and mining/processing technology will be required, including cost-effective uranium extraction techniques for exploiting unconventional deposit types, some of which may become economic given the recent dramatic increase in market prices (e.g. uranium from phosphate and black shale deposits).



Relatively recent innovations and developments that can advance sub-economic and marginal uranium deposits into producing mines include continued progress on the in-situ recovery of uranium from unconformity-type deposits, as demonstrated at the Phoenix deposit in the Athabasca Basin in Canada; the commercial use of surface access borehole resource extraction (SABRE) technology, a new innovative and scalable mining method developed by Orano Canada that allows for the exploitation of relatively small high grade ore bodies that are either too small or too deep to be mined economically by open pit or underground mining methods; and the in-situ bioleaching of sandstone-type uranium deposits, such as at the 512, 721, and 745 uranium mines in China. In addition, heap leaching techniques, which are typically used to extract metals from other types of mineral deposits, continue to be developed and show promise for some uranium operations.

Over the next decade, nuclear fuel production will face increasing demand across all nuclear fuel-related segments due to increasing construction programmes in both established and embarking countries, necessitating the development of new fuel types, including for SMRs and advanced reactors. Some Member States have already planned to develop licensing infrastructure to support the extension of fuel burnup, enrichment beyond the 5% legacy limit and/or enrichment capacities by the late 2020s and to enable the safe and economical operation of 24-month cycles in existing LWRs without physically changing the manufacturing plants or transport containers (i.e., only through changes in licensing procedures).

Many different enhanced fuel designs are being explored, resulting in a large variety of solutions with differing levels of complexity. Some innovative fuels are relatively easy to fabricate using existing fabrication lines and facilities, while others will require the setting up of new fabrication lines and facilities, as they will require enrichment above 5% (LEU+ and HALEU). The successful deployment of all types of SMR fuel will require the maturity of fuel production technologies from the R&D stage to the industrialization stage.

HALEU programmes are being explored in North America, Europe and the Russian Federation. The Russian State Atomic Energy Corporation “Rosatom” has the full infrastructure for industrial HALEU production and the technological capability to produce both LEU+ and HALEU, in various forms, enriched up to 19.75% in 235U. In the USA, efforts to build a HALEU supply chain are under way. The US Department of Energy has established the HALEU Consortium, and Centrus Energy Corp. has begun demonstrating HALEU production. Urenco is preparing to supply LEU+ fuel to international markets. Orano aims to supply enrichment up to 6% by 2025 and up to 19.75% thereafter, depending on demand. The company is also working on transport solutions for UF6 with enrichments of up to 19.75%, as well as for uranium oxides, metals and alloys, using the VP-55 transport package with a high-capacity basket configuration.

B.2. Back End

Status

Spent nuclear fuel (SNF) is accumulating in storage at a rate of approximately 7 000 tonnes of heavy metal (t HM) per year globally, and the stored inventory is around 300 000 t HM. The lifetime extension of some NPPs (e.g., Takahama in Japan or Koeberg in South Africa) contributes to an increase in the amount of discharged SNF.

For countries with well-established nuclear programmes pursuing open cycle strategies, the main challenges remain the requirement for additional SNF storage capacities and the increasing storage duration prior to disposal. In most countries, SNF is moved from wet to dry storage facilities after an initial cooling period. New dry storage facilities have started operation (e.g., in Argentina, Japan, Slovakia and Slovenia). The US Department of Energy has started an initiative for a collaborative-based siting approach to enable the implementation of centralized storage facilities. Member States are continuing with the removal and relocation of their SNF within the framework of NPP decommissioning projects. New technologies have been deployed to improve the inspection of SNF storage facilities and the handling of SNF casks. At Finland’s spent fuel encapsulation plant, major equipment has been installed.

Spent nuclear fuel transportation continues to be a routine operation in some countries. In recent years, new packages for storage and transportation (e.g. TN Eagle, CASTOR geo or TUK-137T.P) have been developed, licensed (e.g. TN Eagle) and put into operation to accommodate new or expanding inventories.

For countries pursuing closed cycle strategies, the main challenges are limited reprocessing capacities and the industrial-scale implementation of multi-recycling in LWRs. The development of new recycling technologies for the current fleet and for advanced reactor fuels continued on a commercial scale in France, India, Japan and the Russian Federation. Currently, about 40 reactors in Europe (in Belgium, France, the Kingdom of the Netherlands and Switzerland) are licensed to use MOX fuel, and over 30 are doing so. In Japan, 4 reactors are licensed to use it and several are doing so. Japan is currently expecting the Rokkasho Reprocessing Plant to begin commercial operation in fiscal year 2026. In the USA, SHINE Technologies is developing advanced fuel recycling processes and had started engaging with the U.S. Nuclear Regulatory Commission on pre-application activities that support the licensing of a proposed pilot facility for the recycling of used nuclear fuel. Oklo Inc. has successfully completed the experimental feasibility study of its fuel recycling process. The operator of the BN-600 fast neutron reactor in the Russian Federation is aiming for a lifetime extension after the inspection of critical equipment. Experimental uranium–plutonium nitride fuel assemblies for BN-1200M will be tested in BN-600 as a further step in the implementation of the 'balanced nuclear fuel cycle' concept, which envisages the reprocessing of SNF, the recycling of regenerated nuclear material as nuclear fuel and the transmutation of minor actinides in fast neutron reactors. In addition, in 2024, three MOX fuel assemblies containing fuel elements with neptunium and americium were loaded into the BN-800 reactor to demonstrate the possibility of burning MA in fast reactors. In 2024, the construction and commissioning of the main facility for the Nuclear Fuel Fabrication and Refabrication Module (NFR) of the Experimental Demonstration Energy Complex (EDEC) were completed. The EDEC Reprocessing Module is being designed. It will use a process flow diagram based on a combination of pyrochemical and hydrometallurgical operations, which allows SNF reprocessing with minimal exposure and obtaining a final product purified from fission products (a mixture of actinides) and suitable for the manufacture of new (regenerated) fuel.

As some SMR designs are based on molten salt fuel (e.g. uranium, plutonium or thorium dissolved in a molten salt), R&D activities on recycling and managing such fuel, including salt clean-up, are being conducted. In the USA, Kairos Power has started construction of a salt production facility after successful salt pump test operations at the Engineering Testing Unit. In France, Orano is considering the possibility to produce and recycle liquid fuel for fast spectrum MSR and has partnered with SMR-type MSR developers in 2024 to work on R&D, pilot installations and logistic solutions for chloride fuel salt. In the Russian Federation, a programme is being implemented to develop and build a 10 MW(e) liquid salt reactor for transmutation of minor actinides at the site of the Mining and Chemical Combine in Krasnoyarsk.

Trends

Knowledge of SNF characteristics and understanding of the behaviour and degradation/ageing of both SNF and storage structures, systems and components remain vital to ensure that SNF can continue to be stored safely and subsequently transported to disposal or reprocessing facilities. There have been continued efforts to better characterize SNF, especially as spent fuel with higher initial enrichments and higher burnups is foreseen, leading to increased thermal outputs and potentially higher risks of cladding embrittlement that may impact the subsequent spent fuel management steps until disposal.

As new fuel designs for both the existing fleet of reactors (e.g., doped fuels) and advanced reactor designs, including SMRs, are envisaged and tested, different behaviours may arise in spent fuel management and innovative solutions will need to be sought to allow for the deployment of these fuels. AGR spent fuel management in the UK and HTGR spent fuel management in Germany provide valuable lessons learned, which could be applied in the management of spent fuels from new HTGR reactors, such as the pebble bed reactor in China.

Due to nuclear power sustainability concerns, there is increased interest in spent fuel recycling. 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 for the sustainable deployment of advanced reactors and SMRs. In France, the back-end strategy has been confirmed beyond 2040 by the Government. Consequently, industrial facilities in La Hague will be extended and new facilities will be built. A new reprocessing plant will be built as of 2045/2050.

The 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. Initiatives to undertake spent fuel and radioactive waste management in an integrated manner are being discussed and implemented in Canada, France and the USA. The development and deployment of new reactors and associated fuel cycles are a major undertaking, and international collaboration and partnership are paramount for success.

C.

Decommissioning, Environmental Remediation and Radioactive Waste Management

C. Decommissioning, Environmental Remediation and Radioactive Waste Management

C.1. Decommissioning

Status

Despite uncertainty regarding future shutdown rates of nuclear facilities, the number of NPPs and research reactors actively undergoing dismantling continues to increase, with a trend towards early dismantling shortly after permanent shutdown. This trend is influenced by government policies, cost reductions from minimizing facility maintenance and surveillance during safe enclosure periods, and concerns over the rising costs of delayed dismantling and associated material management.

The decommissioning of numerous nuclear facilities, including those with multiple power or research reactors, is advancing steadily in many countries, such as Bulgaria, Canada, France, Germany, Italy, Japan, Lithuania, the Russian Federation, Slovakia, Spain, Sweden, the UK and the USA. Notably, countries that have opted for a nuclear phase-out or adopted an accelerated dismantling strategy — such as Germany and the UK — have issued a growing number of decommissioning permits. A further sign of progress is the completed decommissioning of research reactors in countries like Finland and the UK. As of November 2024, 211 power reactors across 21 Member States were shut down for decommissioning, with 23 power units fully decommissioned in Germany, Japan, Switzerland and the USA.

An increased emphasis on circular economy principles is evident in decommissioning projects. Sustainability in decommissioning manifests itself in various ways, including the efficient use of decommissioned materials to minimize waste requiring long term storage or disposal, and a heightened focus on reusing or repurposing sites for future industrial projects. Applying circular economy principles to decommissioning requires collaboration among diverse stakeholders, including policymakers, regulators and local communities, which may have differing perspectives on the future use of nuclear sites.

Despite these advancements, challenges persist, particularly for countries with limited technical and financial resources, which hinders their ability to implement effective decommissioning strategies. Knowledge transfer and international collaboration are vital for sharing best practices and technological innovations, ultimately enhancing global decommissioning outcomes.

As the industry adapts to new developments, SMRs are also influencing decommissioning strategies, potentially simplifying future decommissioning processes thanks to their modular designs.

With their smaller footprints and simplified designs, SMRs may shorten decommissioning timelines and reduce waste compared to larger reactors. However, they also require new regulatory frameworks to address their specific decommissioning challenges. This evolving focus on SMR decommissioning presents opportunities for innovation, particularly in designing for a circular economy. Some SMR developers are exploring designs that emphasize longevity, ease of remanufacturing and the potential for materials to be reused, repurposed or recycled. As more countries consider integrating SMRs into their energy portfolios, collaboration among regulators, industry stakeholders and research institutions will be essential to ensure efficient, safe and environmentally responsible decommissioning processes.

Given this shift, the nuclear decommissioning landscape is expected to evolve over the next few years, calling for continued international cooperation, skills development and technological advancements to manage the varied requirements of reactor types under decommissioning.

Trends

A recent development in NPP decommissioning is the rise of specialized consortia that combine expertise from multiple companies to implement complete decommissioning projects within fixed budgets. These consortia follow standardized approaches and assume the project risks, improving efficiency and cost management.

The deployment of decommissioning technologies continues to advance, with increased reliance on remotely operated tools such as drones and robotics for decontamination, segmentation of facility components, measurements, material handling and automated waste management.

Looking ahead, digital technologies are expected to play a pivotal role in advancing nuclear decommissioning by making insights from current projects more accessible to nuclear facility designers, operators, regulators and future project stakeholders. The broader use of AI will further drive digitalization in nuclear decommissioning. Other innovations include mobile robots for scanning structural and radiological conditions and remotely operated tools for accessing high-dose areas, enhancing safety and operational efficiency.

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

Environmental Remediation

Status

Environmental remediation for radioactively contaminated sites has seen a steady progression worldwide, with many countries implementing frameworks to safely manage contamination and restore affected environments. Member States with advanced nuclear programmes — such as France, Japan and the USA — have established robust remediation programmes focused on decontaminating former nuclear sites, legacy uranium mines and facilities associated with industrial activities. Progress is often achieved through a combination of regulatory standards, technological innovation and collaboration across sectors.

Remediation projects of varying scopes are under way in numerous countries. In the USA, the Department of Energy's Office of Environmental Management oversees the largest environmental remediation programme globally, initially tasked with remediating 107 sites across the country. To date, 92 of these sites have been completed, with 15 still under active remediation. In the UK, the Nuclear Decommissioning Authority is responsible for remediating 17 civil nuclear sites, managing legacy wastes and facilities.

Atomic Energy of Canada Limited manages the Government of Canada's nuclear liabilities, which include five remaining nuclear sites and several uranium mining and processing sites. In Germany, uranium mining and processing sites in Saxony and Thuringia have been remediated since 1991, with nearly 90% of the work completed.

Ongoing remediation of uranium legacy sites in Central Asia is coordinated by the Agency through the Coordination Group for Uranium Legacy Sites. Argentina's Uranium Mining Environmental Restoration Project (PRAMU) focuses on remediating former uranium mining locations and similar progress has been seen in uranium site remediation in France and Portugal.

With regard to nuclear accident sites, extensive and ongoing remediation efforts continue at Chornobyl and Fukushima, where efforts focus on long term containment, monitoring and environmental restoration of contaminated areas.

Trends

Emerging trends in remediation indicate the prioritization of sustainable practices, such as the application of circular economy principles to reduce waste and enhance resource efficiency. Technologies like remote sensing, machine learning and robotics play a significant role, enabling more accurate site characterization, enhanced monitoring and safer waste management. However, for countries with limited resources, challenges remain, making international cooperation crucial to support technical capacity, knowledge sharing and access to best practices.

Environmental remediation presents varied challenges across different Member States. In the case of complex nuclear site remediation, although progress is evident, there are concerns about the pace of work and whether the value of invested resources is fully realized. For countries hosting former uranium mining sites — particularly those with limited resources — the challenge is to find innovative solutions that allow for end states compatible with a productive 'second life' for these sites. Research into advanced technologies and integrated approaches, from site characterization to remediation solutions, remains essential. Innovation is also crucial for the effective valorization of mining tailings.

FIG. C.1. Storage facility for NORM waste from oil and gas operations. (Source: Petrobras)

Looking ahead, the global focus is on sustainable remediation strategies that minimize long term risks to human health and the environment, emphasizing partnerships among governments, industry stakeholders and international organizations. International collaboration is vital for sharing experiences and knowledge that lead to solutions aligned with public expectations, helping to build societal confidence in nuclear energy.

Management of Naturally Occurring Radioactive Material

Status

The global status of NORM management is progressing as countries develop and refine regulatory frameworks to address the unique challenges posed by this material. Many countries, including Canada, the USA and members of the European Union, have implemented specific guidelines for NORM management that address residue handling, storage and disposal in alignment with international standards, with some nations integrating circular economy principles to minimize waste and repurpose materials where possible. Advanced technologies such as artificial intelligence and data-driven inventory management are increasingly used to track and manage NORM.

Lower-income countries with disparities in resources and technical expertise face greater challenges in implementing comprehensive NORM management. International cooperation and knowledge sharing remain essential to support countries in establishing effective frameworks and addressing the health, safety and environmental impacts of NORM residues.

Trends

The management of NORM remains a challenge for many Member States, particularly those needing to decommission offshore oil and gas platforms. Holistic management approaches, incorporating policy and strategy and supported by comprehensive residue inventories and cost-effective disposal routes for NORM wastes, are essential. Implementing circular economy solutions for generated residues will also be a key enabler, helping Member States achieve safe, sustainable and timely decommissioning outcomes.

C.3. Radioactive Waste Management

Status

Significant progress in radioactive waste management continued throughout 2024, with notable advancements in disposal programmes and the ongoing safe application of predisposal technologies. These efforts underscore a commitment to long term waste management solutions that prioritize safety and environmental protection.

RADON-type storage facilities are being decommissioned in several countries. Lithuania has already retrieved waste and contaminated materials from the Maišiagala facility, aiming for site release by mid-2025. In Hungary, plans are under way to remove and relocate waste from the Püspökszilágy site to the Bátaapáti repository. The Republic of Moldova is also preparing to decommission its RADON-type facility in 2026–2027.

Characterization capabilities have been developed by the Pakistan Atomic Energy Commission for both NPP waste and decommissioning waste. In parallel, tailored processing technologies for ion exchange resins are under development, with careful consideration given to waste minimization through the deployment of supercompaction and incineration facilities.

FIG. C.2. Infrastructure for decommissioning the RADON-type storage facility at Maišiagala, Lithuania. (Source: Ignalina NPP)

FIG. C.3. Characterization laboratory and operational waste conditioning at Chashma NPP, Pakistan. (Source: PAEC)

Many Member States continue to develop and refine national policies and strategies for radioactive waste management, alongside setting up dedicated waste management organizations. In Türkiye, the Turkish Energy, Nuclear and Mineral Research Agency (TENMAK) was established to oversee the entire lifecycle of radioactive waste management, while Armenia and Portugal are also advancing in developing a legal framework for the creation of waste management organizations.

Bulgaria's Radioactive Waste State Enterprise (DPRAO) completed construction of the National Disposal Facility in June 2024. The facility, located near Kozloduy NPP, is under inactive pre-commissioning testing. It is a state-of-the-art facility designed and constructed for the disposal of operational and decommissioning low and intermediate level radioactive waste generated from the NPP.

In July 2024, France's Industrial Centre for Collection, Storage and Disposal (CIRES) was granted an authorization for an extension of its disposal capacity from 650,000m3 to 950,000m3 without any surface increase. This will extend the center's operating life by around 15 years.

In the Russian Federation, research is being conducted on the separation of the "short-lived fraction" of caesium and strontium isotopes from SNF with the possibility of conditioning them into matrices acceptable for near-surface disposal, thereby reducing by an order of magnitude the volumes and activity of deep disposal of radioactive waste. In addition, a plan is in place to establish a laboratory in the Krasnoyarsk region to test the technology for deep underground disposal of high and intermediate-level waste.

Slovenia's Agency for Radwaste Management (ARAO) has started construction of a disposal facility for low level radioactive waste generated by the operation and future decommissioning of Krško NPP. The first-of-its-kind concrete-lined silo-type facility is being constructed from the surface down. When finished, it will have an interior diameter of approximately 27 m and a depth of about 51 m. The facility is expected to be completed in 2027 and is planned to operate until the mid-2040s.

FIG. C.4. Construction of the disposal facility for low level radioactive waste begins in Slovenia. (Source: ARAO)

Exciting developments took place in deep geological repositories even as siting and licensing such facilities remain as challenging for such facilities. The Swedish Nuclear Fuel and Waste Management Company received permission to 'go underground' and begin deep geological repository construction at Oskarshamn. In Finland, the Onkalo repository stands out as the project is nearing operational readiness. Posiva started a final disposal trial run in August 2024 at the Onkalo final disposal facility for spent nuclear fuel in crystalline host rock in Olkiluoto. The trial run involves the encapsulation of five copper–cast iron canisters containing dummy fuel assemblies. Six waste management organizations and one Member State authority are attending the trial run via Posiva Solutions for a fee. Canada's Nuclear Waste Management Organization launched its community-driven, consent-based site selection process in 2010 and in November 2024, announced that it had selected Wabigoon Lake Ojibway Nation and the Township of Ignace located in the province of Ontario as the host communities for the future site for Canada's deep geological repository. In France, the 'Cigéo' deep geological radioactive waste repository project is undergoing the necessary public consultation and technological assessment processes and is advancing on schedule. Construction is expected in 2027-2028 and its operation from 2035 onwards.

Trends

Integrated radioactive waste management supports the sustainable use of nuclear technology by optimizing waste handling, from waste generation to disposal. This approach streamlines processes and mitigates environmental risks, and requires coordination between policymakers and waste management operators to set effective goals and select suitable technical solutions.

The US Department of Energy (DOE) has concluded a two-year study related to the long-term management of spent nuclear fuel from advanced reactors. This study will inform the DOE's negotiations with future reactor operators related to the conditions under which DOE would accept spent nuclear fuel.

FIG. C.5. Trial operations for spent fuel disposal in Finland aim to test the whole disposal system, including technology, organization and procedures. (Source: Posiva Finland)

Member States' growing interest in deploying SMRs is expected to reshape nuclear industry, but it also introduces new challenges in the area of radioactive waste management. As countries adopt SMR technology, radioactive waste management policies and strategies must adapt accordingly. The core issue lies in having a clear understanding of the waste profiles — specifically the types, volumes and radioactivity levels of the waste produced by SMRs. This knowledge is crucial for developing effective waste management systems, including processing, storage and disposal solutions tailored to the unique characteristics of SMR waste.

Another emerging trend is the adoption of the radioactive waste hierarchy, which places an emphasis on waste prevention, minimization, reuse and recycling. This approach reduces the volume of radioactive waste destined for disposal facilities, enabling 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 LEU further demonstrates a commitment to waste reduction. France's National Plan for the Management of Radioactive Materials and Waste aims at providing an integrated multiannual strategy for nuclear waste management, with a view to reducing volumes of waste and improving the circularity of the nuclear sector.

The Global Radium-226 Management Initiative is set to recycle legacy radium sources. Under this initiative, disused radium sources were removed from El Salvador, Slovenia and Thailand. Another eight transfers are in the pipeline, including from Fiji, Indonesia, Malaysia, the Philippines and Sri Lanka, with a view to taking stock of available disused radium sources for radioisotope production for cancer treatment. In 2024, a total of 11 high activity sources were removed from the Dominican Republic, Jordan and the Republic of Moldova. Member States continue to request technical support for Category 1 and 2 source removal involving complex and larger inventories following a successful operation in Chile in 2023.

D.

Fusion Research and Technology Development for Future Energy Production

D. Fusion Research and Technology Development for Future Energy Production

Status

Progress continued at the National Ignition Facility in the USA. Since the fusion energy ignition breakthrough in December 2022, researchers at the US Lawrence Livermore National Laboratory have successfully replicated this achievement at least four times. Four subsequent experiments in 2023 and early 2024 repeated ignition, with the most recent producing a record yield of 5.2 megajoules and a gain greater than 2.

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 during the period of operation.

In its final experiments in December 2023, JET achieved a groundbreaking milestone. Scientists set a world record by maintaining sustained fusion for 5 seconds, generating 69 megajoules of energy with minimal fuel. They explored innovative techniques, such as inverting the plasma shape to enhance its confinement. Additionally, they intentionally directed a high energy beam of electrons, produced during plasma disruptions, at the inner wall to advance understanding of beam control and wall material damage mechanisms.

The ITER project has gone through a period of transition and is moving forward on the basis of a new project baseline. Repairs to key components are progressing according to schedule. Progress has continued on construction, manufacturing,

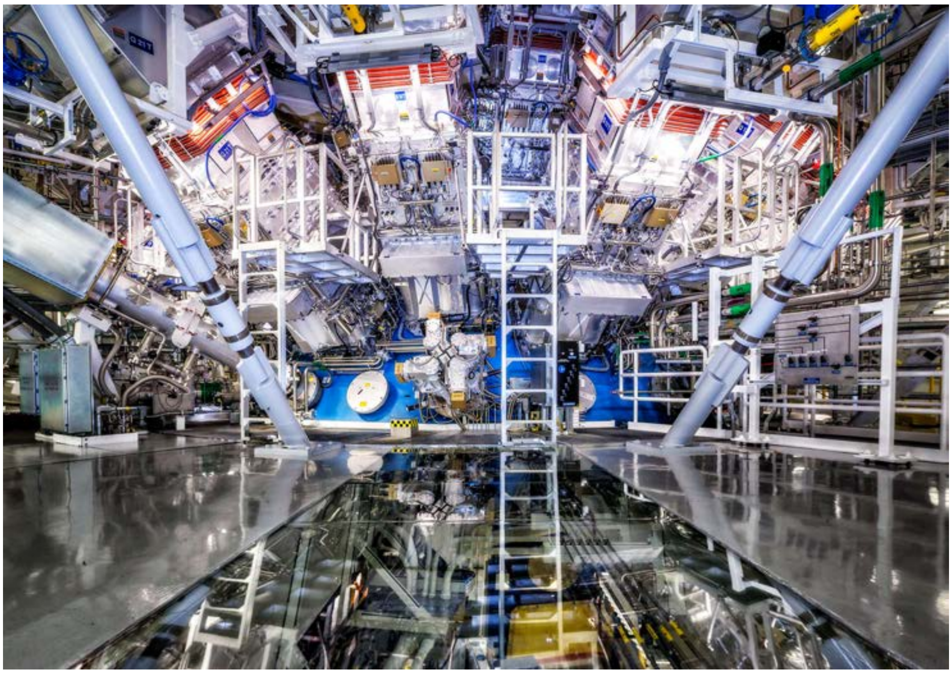


FIG. D.1. National Ignition Facility at the Lawrence Livermore National Laboratory, USA. (Source: Lawrence Livermore National Laboratory)

FIG. D.2. The repurposing of JET will be aided by remote handling systems. (Source: United Kingdom Atomic Energy Authority)

FIG. D.3. Aerial view of the ITER site as of July 2024. (Source: ITER Organization)

assembly and system commissioning. Following more than a year of review, a new baseline proposal was submitted to the ITER Council in June 2024, and in November 2024, the Council endorsed the overall approach proposed for Baseline.

The discovery and analysis of geometric non-conformities in the bevel joints of several vacuum vessel sectors, as well as chloride corrosion cracking in the cooling pipes of the thermal shields, led to a slowdown in ITER tokamak assembly while the necessary repairs were being carried out. Extensive discussions were held with the French nuclear safety authority (ASN) to enhance the safety demonstration accompanying ITER's licensing. Meanwhile, the power supply systems, cryogenics plant and cooling water system have been installed and largely commissioned. All poloidal and toroidal field coils, as well as most of the central solenoid modules and other major components have been delivered.

FIG. D.4. Inside the HH70 tokamak, which started operating in June 2024. (Source: Energy Singularity)

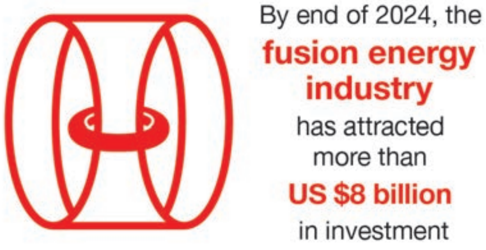
FIG. D.5. Director General Rafael Mariano Grossi visiting the Princeton Plasma Physics Laboratory, University of Princeton, USA. (Source: IAEA)

The largest task over the past year has been to channel these elements into a realistic updated project baseline. In the resulting proposal, the previously envisioned assembly and operation stages are consolidated. Technical and operational risks are mitigated by incorporating the divertor, shield blocks, a sacrificial first wall and other risk-reducing components into a more complete machine before initial operation, and by fully testing some toroidal and poloidal field coils before installation. The start of research operations (SRO) in 2034 will mark the beginning of a 27-month period of substantial experimentation with hydrogen and deuterium–deuterium plasmas, which will culminate in the operation of the tokamak in long pulses, at full magnetic energy and plasma current (15 megaamperes), in 2036. The SRO phase will largely demonstrate the integration of systems needed for industrial-scale fusion operations. The start of deuterium–tritium operations will be delayed by four years from the previous baseline, from 2035 to 2039.

The State Atomic Energy Corporation "Rosatom" has developed a preliminary design for a reactor technology tokamak (RTT). The implementation of the RTT project will allow Russia to develop and apply the knowledge and experience gained during the implementation of the ITER project.

HH70, the world's first high temperature superconducting (HTS) tokamak, developed by Chinese company Energy Singularity, has achieved its first plasma. The device has a toroidal magnetic field of 0.6 Tesla and a major radius of 0.75 metres, and a system of 26 HTS magnets. Looking ahead, Energy Singularity is planning its next generation high field HTS tokamak, HH170, which aims to achieve a deuterium–tritium equivalent energy gain greater than 10.

Trends



Governments across the globe are recognizing the potential of fusion energy and are investing heavily in R&D to propel progress. National strategies are being developed — accompanied by substantial funding allocations — to support both public and private sector initiatives, the development of initial regulatory frameworks and increased engagement with supply chains. Collaborative efforts are also on the rise, with countries entering into agreements to share knowledge, resources and infrastructure to accelerate progress towards commercial fusion energy production. The synergy between scientific breakthroughs and supportive policy frameworks is creating a robust ecosystem aimed at making fusion energy a reality in the near future.

The fusion energy industry is experiencing consistent year-on-year investment growth. While the majority of investments (around 70%) have historically been directed towards fusion companies in the USA, 2023 marked a notable expansion in equity investments in fusion companies across a broader range of countries. These countries include Canada, China, France, Germany, Israel, Japan and Sweden, reflecting a global surge in interest and funding for fusion energy development. The fusion energy industry has now attracted more than US $8 billion in investment.

Regulatory bodies and lawmakers are increasingly addressing the challenges and opportunities presented by fusion energy. In July 2024, the US Government enacted a law —the ADVANCE Act—which incorporates provisions from the bipartisan Fusion Energy Act and aims to facilitate the development of commercial fusion energy by providing clear regulatory authority and incentives for investment. These provisions support the Nuclear Regulatory Commission's earlier decision to separate fusion energy regulation from that of fission energy, regulating near-term fusion energy systems under the by-product material framework, which is currently applied to particle accelerators. In 2023, California became the first US state to recognize fusion energy as a separate and distinct

FIG. D.6. IAEA Director General Rafael Mariano Grossi with Member State delegates at the inaugural ministerial meeting of the World Fusion Energy Group, Rome, Italy, 6 November 2024. (Source: IAEA)

technology from fission energy. The Nuclear Regulatory Commission is in the process of drafting licensing guidance for fusion systems.

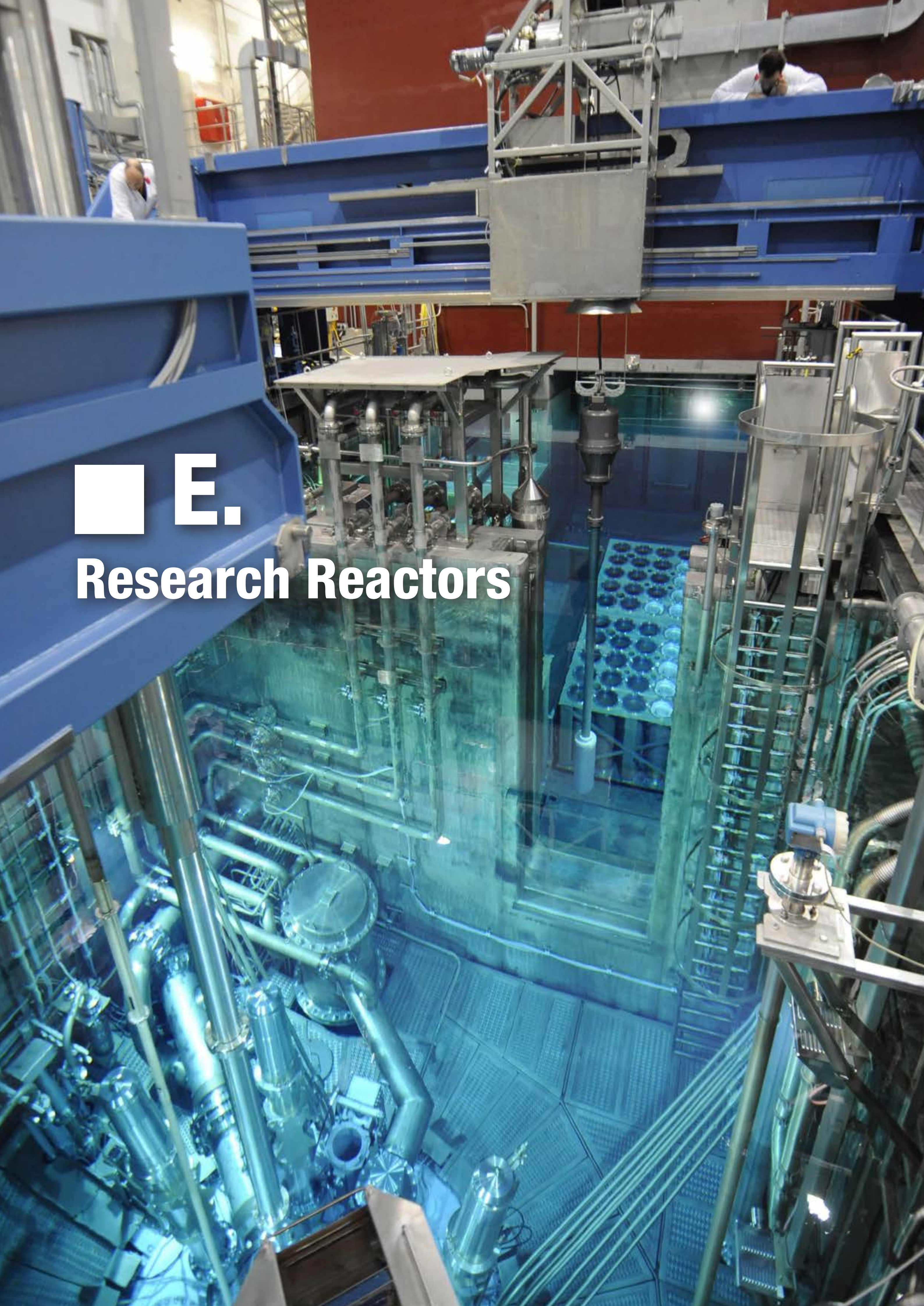
The UK Government confirmed that all planned prototype fusion energy facilities in the country would continue to be regulated by the Environment Agency and the Health and Safety Executive, unlike NPPs, which are regulated by the Office for Nuclear Regulation.

In addition, the Agile Nations working group on fusion energy, comprising Canada, Japan and the UK as members, with Bahrain and Singapore as observers, produced joint recommendations. These recommendations recognize the important contribution that fusion energy could make to addressing global challenges relating to climate change and energy security, as well as the benefits of adopting a harmonized approach to fusion energy regulation across several countries; and advocate clarity on a regulatory framework that would apply to fusion energy facilities independent of the fusion technology and that would maintain appropriate protections for people and the environment, proportionate to the hazards of fusion energy, while remaining transparent and pro-innovation.

Germany is following a similar path. A public hearing of the Committee on Education, Research, and Technology Assessment held in 2024 highlighted the need for a pragmatic, innovation-friendly and independent legal framework for fusion energy, aimed at encouraging private investment and supporting the development of markets for fusion technologies. Meanwhile, France considers that fission and fusion share nuclear common technical and regulatory challenges, and for this reason, that the development of the latter should capitalize on the existing regulatory and governance framework that applies to the former.

To enhance collaboration across the fusion sector, the Agency announced the establishment of the World Fusion Energy Group. The Group aims to unite scientists, engineers, policymakers, financiers, regulators and private companies to accelerate the commercialization of fusion energy. The inaugural ministerial meeting of the Group was held on 6 November 2024 in Rome and was organized by the Agency and the Government of Italy.

■ E.
Research Reactors



E. Research Reactors

Status

There were 234 operational research reactors, including those in temporary shutdown, in 54 countries at the end of 2024. These research reactors continued to generate neutron beams, provide indispensable irradiation services for science, medicine and industry, and enhance education and training programmes. The most frequent applications of research reactors are shown in Table E-1 in the Annex.

Eleven new research reactors 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.

At the end of 2024, 13 Member States had formal plans to construct new research reactors, namely Bangladesh, Belarus, Belgium, China, India, the Kingdom of the Netherlands, Nigeria, South Africa, Tajikistan, Thailand, the USA, Viet Nam and Zambia. In addition, a significant number of countries were considering building research reactors, namely Azerbaijan, Ethiopia, Iraq, Kenya, Malaysia, Mongolia, Myanmar, Niger, Rwanda, Senegal, Sudan, Tunisia, Türkiye, Uganda, the UK and the United Republic of Tanzania.

International efforts continued to minimize high enriched uranium (HEU) use in the civilian sector. All major global producers of the most in-demand medical radioisotope molybdenum-99 have stopped using HEU targets. To date, 109 research reactors and medical isotope production facilities have been converted from the use of HEU to LEU or confirmed as being shut down, and 6934 kilograms of HEU have been repatriated to their country of origin or otherwise dispositioned from 48 countries (plus Taiwan, China).

The global production and improper disposal of plastics has resulted in massive amounts of microplastics and nanoplastics, which have become a ubiquitous air, water and land pollutant and a threat to natural ecosystems and human health. Microplastics and nanoplastics result from the fragmentation of a variety of products, which affects their morphology, internal dynamics and the way they respond to external stimuli. Thanks to their sensitivity to light elements, neutrons can be used as probing particles in research into plastic pollution. Neutron imaging not only allows for the identification of microplastics, but also provides valuable information on their shape, size and distribution in sediments or soil. Small angle neutron scattering (SANS) is a powerful non-destructive technique for studying the structure of materials at the mesoscopic scale, down to few nanometres. Furthermore, time-resolved SANS makes it possible to study, in situ and in real time, structural evolution during both the synthesis and disintegration of polymeric nanoparticles. It is believed that nanoparticles can enter human cells. In this regard, cold, thermal and epithermal neutrons are ideal probes to study live cells and modifications in membrane properties caused by polymers, nanoparticles, nanoplastics and others. The Agency's Interactive Map of Neutron Beam Instruments reports 55 neutron imaging facilities in 35 Member States and 372 neutron scattering instruments in 26 Member States operating at both research reactor- and accelerator-based neutron sources, providing infrastructure and capacity for a promising holistic approach to ensuring a circular and sustainable plastics system.

FIG. E.1. Installation of the reflector tank at the RA-10 research reactor, Ezeiza Atomic Centre, Argentina. (Source: National Atomic Energy Commission (CNEA), Argentina)

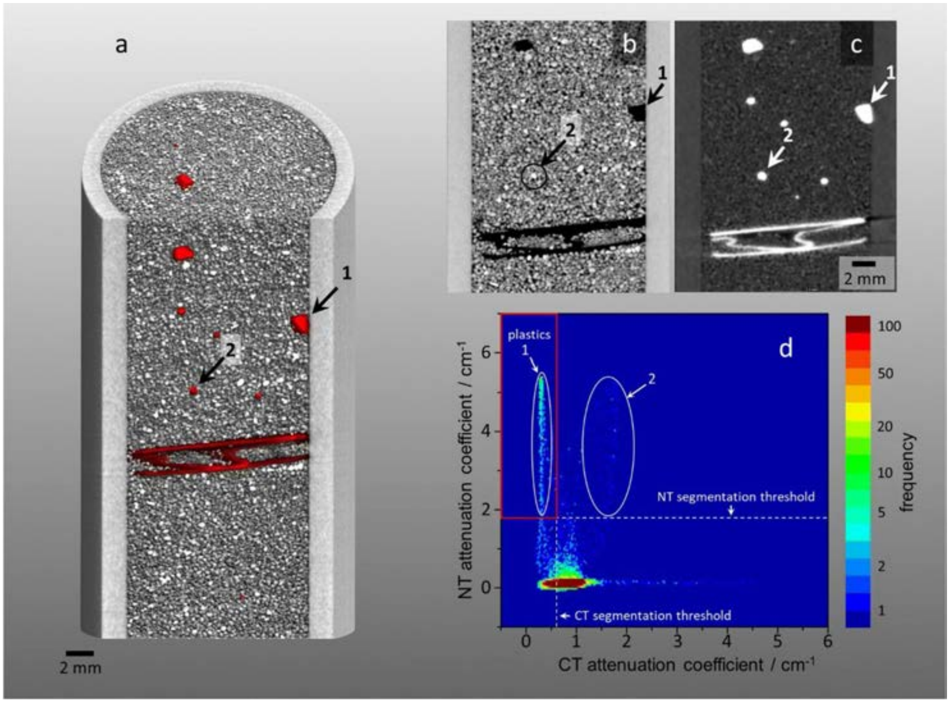
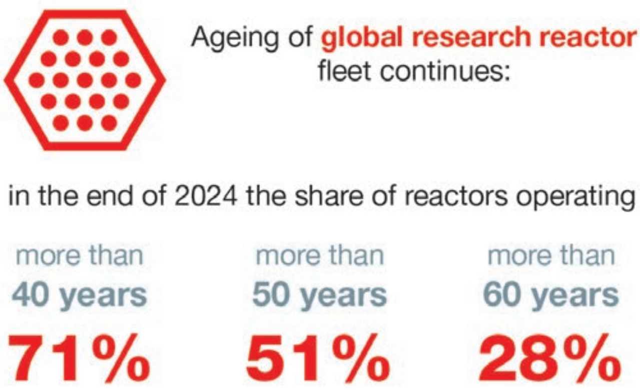


FIG. E.2. 3D rendered image combining neutron and X-ray tomography. The sub-volume containing a plastic particle is labelled '1'. (Source: J Soils Sediments 21, 1476 (2021)[1])

1 TÖTZKE, C., OSWALD, S.E., HILGER, A. et al. Non-invasive detection and localization of microplastic particles in a sandy sediment by complementary neutron and X-ray tomography. J Soils Sediments 21, 1476–1487 (2021). Available at https://doi.org/10.1007/s11368-021-02882-6.

Trends

The ageing of the global research reactor fleet continues: at the end of 2024, the share of reactors operating for more than 40 years was 71%, the share operating for more than 50 years was 51%, and the share operating for more than 60 years was 28%. Even beyond the age of 60, many research reactors, including high power reactors, demonstrate safe operation and effective utilization, serving as major sources of radioisotopes for medicine and industry, basic facilities for testing new nuclear fuels and materials, and intense neutron sources for advanced neutron beam research. Examples include the LVR-15 reactor in the Czech Republic, the Budapest Research Reactor in Hungary, Belgian Reactor 2, the SM-3 reactor in the Russian Federation, the High Flux Reactor in the Kingdom of the Netherlands, and the CABRI reactor in France. Continued safe operation was made possible by regular ageing management, refurbishments and modernization programmes implemented at the facilities. Extensive modernization campaigns are also under way at the MARIA reactor in Poland and the RECH-1 reactor in Chile, which both marked their 50th anniversaries in 2024.



The growing global interest in nuclear power has led to increased demand for nuclear education and training using research reactors. Along with national programmes and capacity building mechanisms facilitated by Agency, such as Research Reactor Schools, Internet Reactor Laboratories and IAEA-designated International Centres Based on Research Reactors, several university research

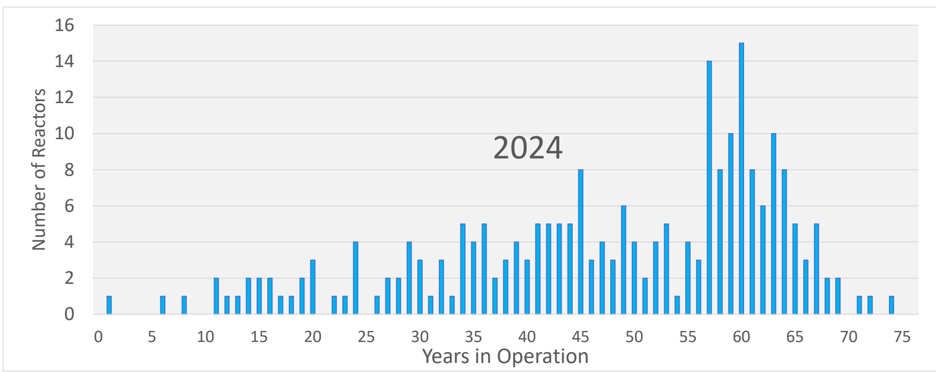


FIG. E.3. Age distribution of operational research reactors, November 2024. (Source: IAEA Research Reactor Database)

FIG. E.4. IAEA Director General Rafael Mariano Grossi visiting the Tashkent Institute of Nuclear Physics, December 2024. (Source: Institute of Nuclear Physics, Tashkent)

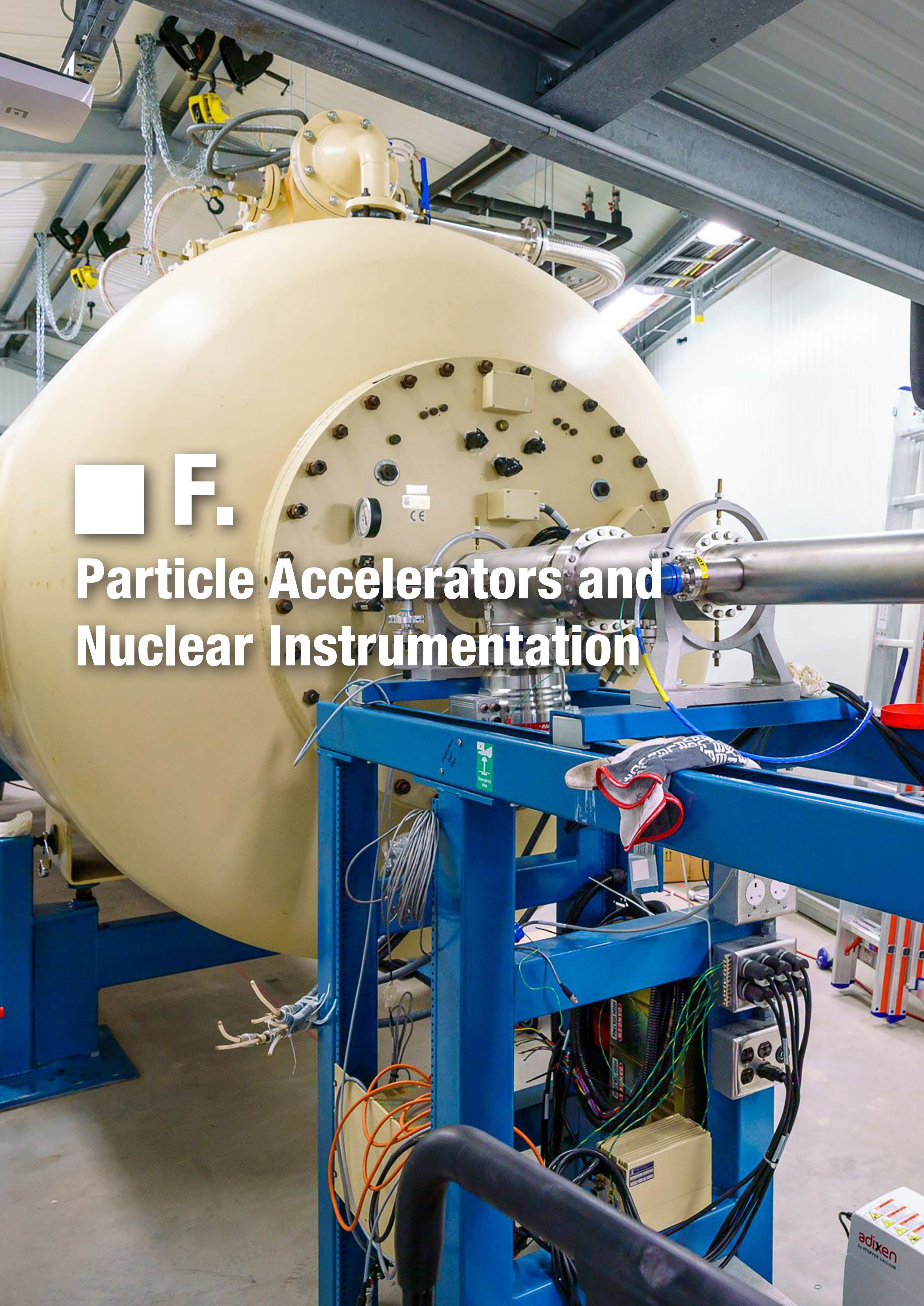
reactors in Europe and the USA are expanding their hands-on training offerings for international customers.

Neutron transmutation doping of silicon (NTD-Si) is an important method for making high-quality silicon semiconductors. Developed in the 1970s, NTD-Si technology involves exposing silicon ingots to a controlled flux of neutrons in research reactors (see FIG. E.5). The main global producers are quite limited, as only a few high performance facilities can provide the required irradiation services and contribute to the supply chain on an industrial scale.

Demand for high power electronic components made using NTD-Si has been growing significantly, driven by the expansion of the power grid infrastructure, industrial automation, wind turbine systems, high speed trains and the automotive industry sectors, among others. These sectors rely on efficient, high performance materials, making NTD-Si a critical resource. As a result, ensuring a steady supply of NTD-Si in the future is essential for supporting technologies that reduce carbon emissions, thus helping to achieve net zero targets and combat climate change.

FIG. E.5. Silicon ingots of different dimensions— one of the irradiation products from the OPAL research reactor in Australia. (Source: Australian Nuclear Science and Technology Organisation)

F. Particle Accelerators and Nuclear Instrumentation



F. Particle Accelerators and Nuclear Instrumentation

F.1. Particle Accelerators

Status

Ion implantation is a physical process used to modify the properties of materials of high technological interest. In this process, subatomic charged particles (ions) are accelerated by sophisticated devices known as implanters before impinging on the surface of materials (see FIG. F.1) with specific physicochemical properties. As such, ion implantation is a nuclear technique based on particle accelerators.

The applications of ion implantation are diverse, covering almost all fields of modern technology — from the production of semiconductors for industrial purposes (e.g., microchips) to the modification of materials used in spacecraft construction. There is a continuously increasing demand for implanters capable of manufacturing components for specialized telescopes and image sensors. Groundbreaking research, such as the investigation of planetary grain erosion, also benefits from this advanced technique. Financial sustainability studies have shown that operating an ion implantation facility can be a highly profitable business. This is due partly to the relatively small footprint required for the necessary infrastructure, resulting in lower operational costs compared to other industrial accelerator-based facilities. The vast potential for innovation and socioeconomic development offered by ion implantation facilities is both unique and undeniable. As the costs of establishing ion beam implantation facilities gradually decrease, less developed countries could capitalize on the numerous applications of this technology in the future.

FIG. F.1. Focused ion beam provided by an ion implantation accelerator. (Source: Adobe Stock)

Trends

Several international projects are aiming to establish a permanent human presence on the Moon and to reach Mars and beyond within the next few decades. During these deep space missions, astronaut crew members will be exposed to highly energetic particles as a result of galactic cosmic rays and solar energetic particles, as illustrated in FIG. F.2. Energetic particles can be dangerous to humans because they pass right through the skin, depositing energy and damaging cells or DNA along the way. In addition, space radiation

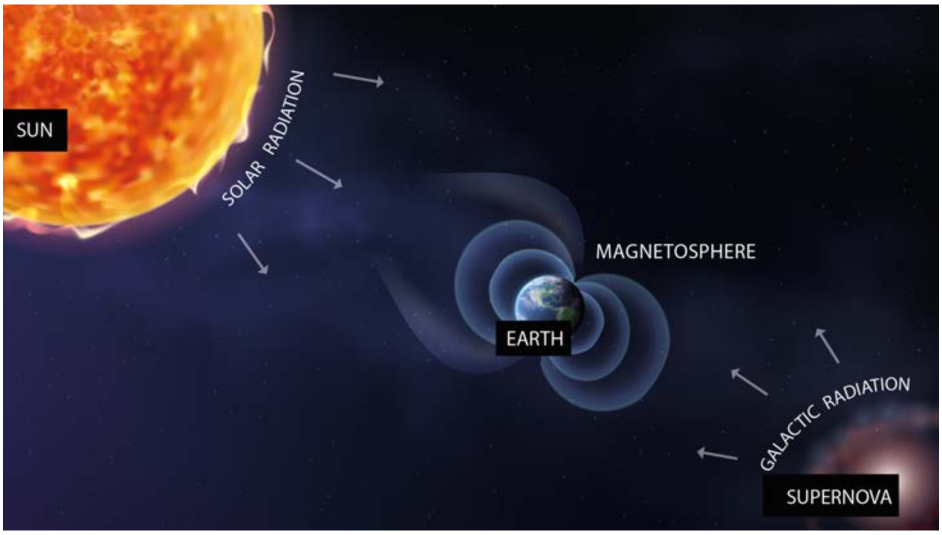


FIG. F.2. Space radiation may pose significant risks to both astronauts and spacecraft. (Source: Adapted from Cosmic Radiation: Why We Should Not Be Worried | IAEA)

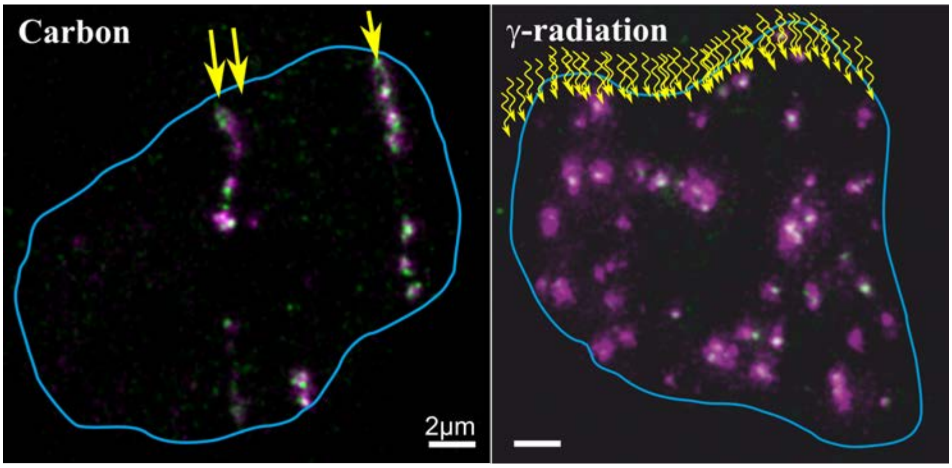


FIG. F.3. DNA damage, visualized by repair proteins (magenta and green), induced by three carbon ions in a human cell nucleus (blue line), and irradiated by the tandem accelerator at the Maier-Leibnitz Laboratory, Garching, Germany. The damage induced by carbon ions, which are part of space radiation, is clustered along the flight path. The severe, complex and localized damage to the DNA poses a higher risk of cell damage — such as genetic alterations, which can lead to cancer, or cell death — compared to radiation on Earth. For comparison, a cell nucleus (blue line) irradiated with the same dose of gamma radiation is shown. Here, the damage is homogeneously distributed, which makes it much easier for the cell to repair. (Source: Judith Reindl, University of the Bundeswehr Munich, Germany) can alter operation of electronic devices and systems through single event effects caused by the typically heavy ion component of cosmic rays and by high energy protons. It is crucial to understand the cause and frequency of these events, in order to reduce the risk of component failure and develop reliable electronic systems.

Protons and heavy ions can be accelerated to high energies in an ion beam accelerator in order to create irradiation damage (see FIG. F.3) at specific energy levels by simulating the effects of radiation exposure in space. The relevant radiation dose delivered by particle accelerators in minutes is equivalent to irradiation in space over years. Hence, such irradiation and testing capability is of great importance for planning deep space missions when it comes to conducting research on radiobiological effects, the radiation hardening of electronic devices and shielding materials.

The main areas in which ion beam accelerator science helps in space exploration are dosimetry in the mixed radiation environment, shielding to mitigate radiation exposure, the hardening of electronic devices, and improving understanding of the biological effects of space radiation. The results of such research also support improved cancer therapy and the development of electronic systems with improved performance and reliability in harsh radiation environments. Among other activities, the Agency is pursuing accelerator science applications for radiobiology and detector development through a CRP entitled "'Sub-cellular Imaging and Irradiation using Accelerator-based Techniques".

F.2. Nuclear Instrumentation

Status

Recent advancements in neutron and gamma ray detector technology have led to compact, energy-efficient, dual-functional systems vital for space exploration. These detectors facilitate hydrogen mapping and elemental analysis on celestial bodies, such as the Moon and Mars. By analysing fast neutrons and gamma ray emissions from cosmic ray interactions, scientists can infer the presence of water and rare elements. Notably, new scintillator materials, like caesium-lanthanum-lithium-bromo-chloride (CLLBC), enhance sensitivity and energy resolution in extreme conditions. These innovations support lightweight, multifunctional designs, improving the effectiveness and simplicity of payloads for planetary science missions. FIG. F.4 shows a preliminary design of a detector module based on a scintillator crystal, an array of silicon photomultipliers and the ROSSPAD readout module. A recent study showed that CLLBC coupled with the ROSSPAD system offers better performance compared to other scintillators used in gamma ray and neutron detection.

Furthermore, the incorporation of multichannel, space-grade application-specific integrated circuits (ASICs) in such dual neutron and gamma ray detection systems contributes to improved noise reduction, enhanced data processing speeds and prolonged operational lifespans in extreme space conditions. Such technology, as seen in offerings from prominent space-tech companies, provides compact and high performance solutions that enhance data acquisition and reliability, facilitating long term extraterrestrial missions and reducing the need for frequent maintenance or replacements. The synergy of hybrid scintillation materials and advanced space-grade ASICs exemplifies a consolidated trend

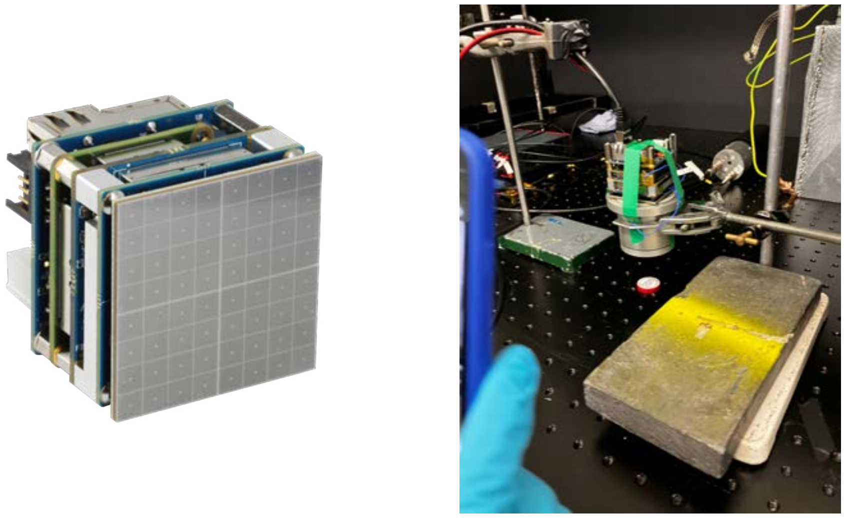
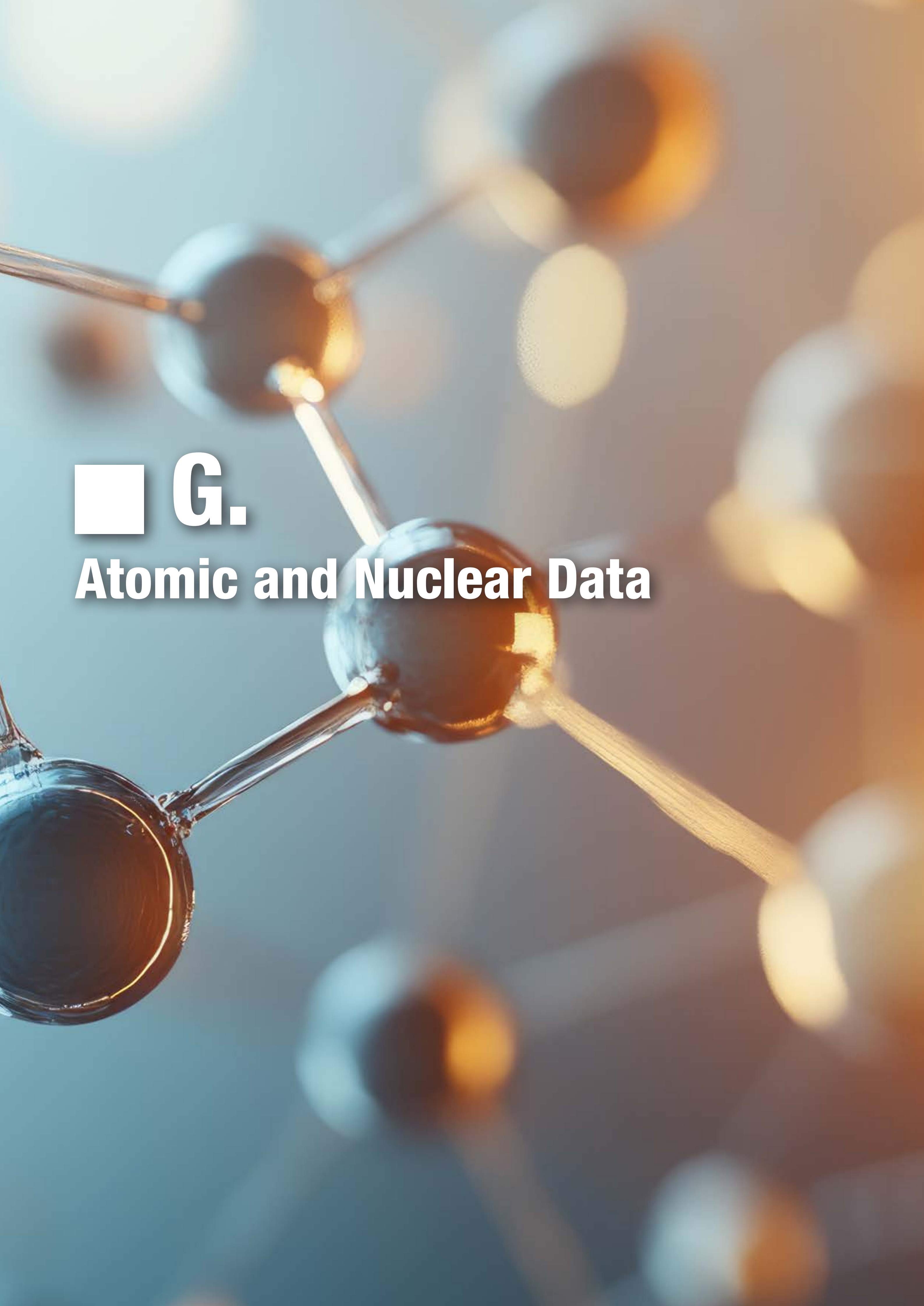


FIG. F.4. Compact scintillator-based gamma-ray neutron detector for terrestrial and space applications (ROSSPAD system) and experiment setup for testing purposes. (Source: Department of Technology Systems, University of Oslo, Norway)

towards multifunctional, durable detection systems for space exploration. These advancements enable detailed, real-time analysis of planetary compositions, supporting missions aiming to uncover water resources and other elemental data critical for future lunar and planetary exploration initiatives.

Trends

Various radiological and nuclear security applications require the fast and reliable identification of radionuclides in unknown samples or matrices. Although the analysis of gamma ray spectra is a straightforward task, in practical field use, when the radionuclides present and their internal configuration or shielding are a priori unknown, the development of dedicated reconstruction algorithms for different types of detectors is challenging. Difficulties arise, inter alia, because field applications often use low resolution detection systems; some radionuclides may be near the limit of detection; a mixture of high intensity and low intensity sources can be present in one sample; and shielding, which is often unknown, affects the line ratio in radionuclides with more than one significant gamma ray. Recently, the rapid development of various machine learning methods has led to their use in gamma spectroscopy for radioisotope identification. Artificial neural networks are particularly well suited to the analysis of complex data, thanks to their superior pattern recognition capabilities. Several related studies have been conducted in different Member States, with promising results, while research recently conducted by Portuguese scientists in collaboration with the Agency's Nuclear Science and Instrumentation Laboratory produced better results when compared to conventional automated gamma spectroscopy software employed for spectral analysis and radionuclide determination. Industrial applications of these methods will require the implementation of qualification processes and acceptance before they can be used routinely.



G. Atomic and Nuclear Data

G. Atomic and Nuclear Data

Status

Fusion research requires a comprehensive database that offers extensive data on plasma collision processes, including cross sections and rate coefficients for collisions between electrons, photons and heavy particles, supporting accurate modelling and simulation for fusion power plant design. The Agency provides and curates fundamental scientific data for fusion power plant modelling processes, as depicted in FIG. G.1. For the past year, the Agency's fusion data webpages have been accessed by visitors from 163 Member States, with most visits from China, India and the USA. The data provided is used for fusion fuel plasma simulations and the modelling of crucial processes between the plasma and reactor wall components.

ITER is in its engineering phase and is a fusion data 'mega-user'. For several years, ITER and its collaborators have been relying on the Agency's fusion neutron data libraries, but recently ITER has also shown great interest in the Agency's fusion databases on plasma collision and plasma-wall interaction processes. Based on this direct interaction between the Agency and ITER, the database of plasma collision processes has been integrated in a public application programming interface (API), enabling selective mass downloads or a bulk download of the whole database. Similar functionalities are planned for the database of plasma-wall interaction processes with a view to providing maximum public access to the Agency's fusion data.

Trends

Following the general worldwide trend in data science, nuclear and atomic data for nuclear science and technology are increasingly handled by APIs that allow programmatic access to the data for direct application in software such as machine learning algorithms. This is in addition to the graphical user interfaces that have been used in past decades, and will continue to be used. The most advanced APIs in this field are those used for nuclear structure and decay data and data relating to atomic collisions inside the fusion plasma. The Agency is following up on this by revising its most important historical nuclear databases, like the EXFOR and ENDF data libraries, and making them available in a unified format for automated processing by users.

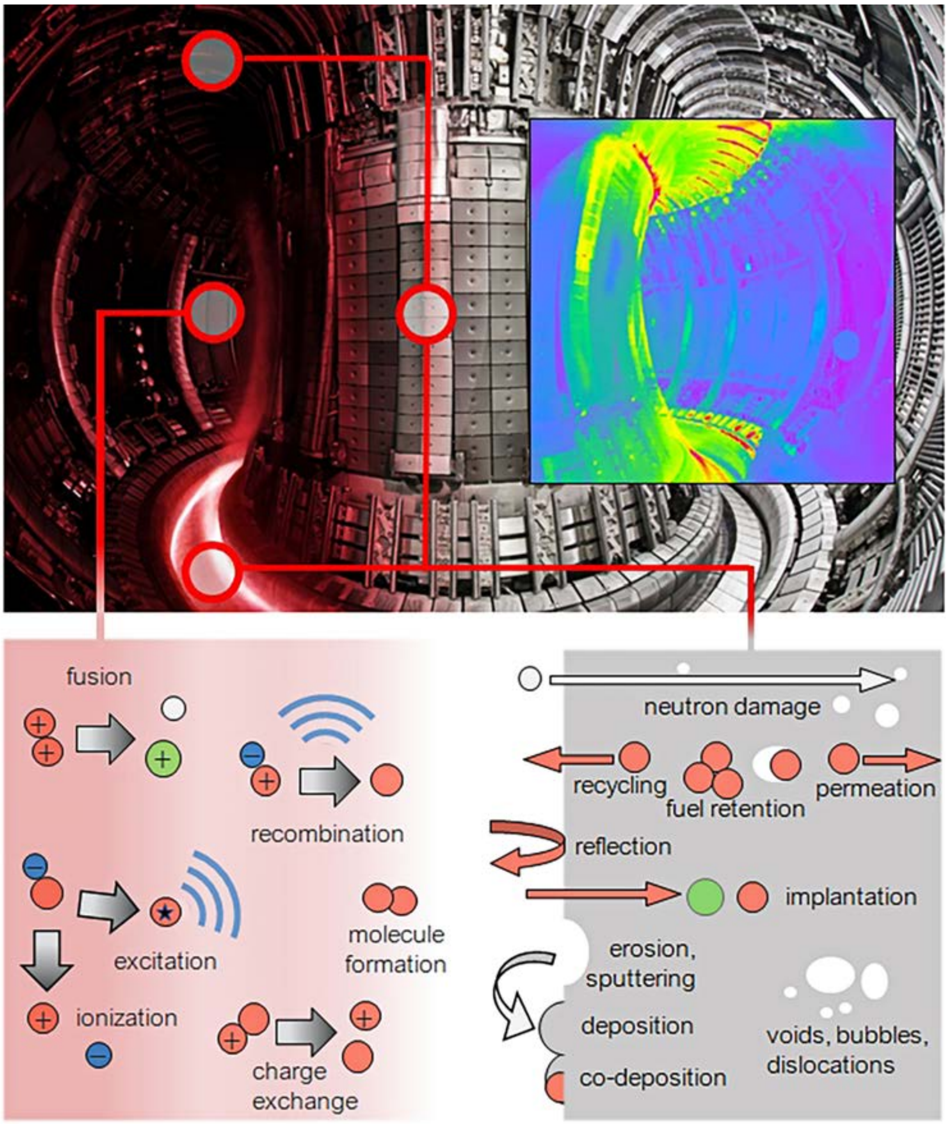


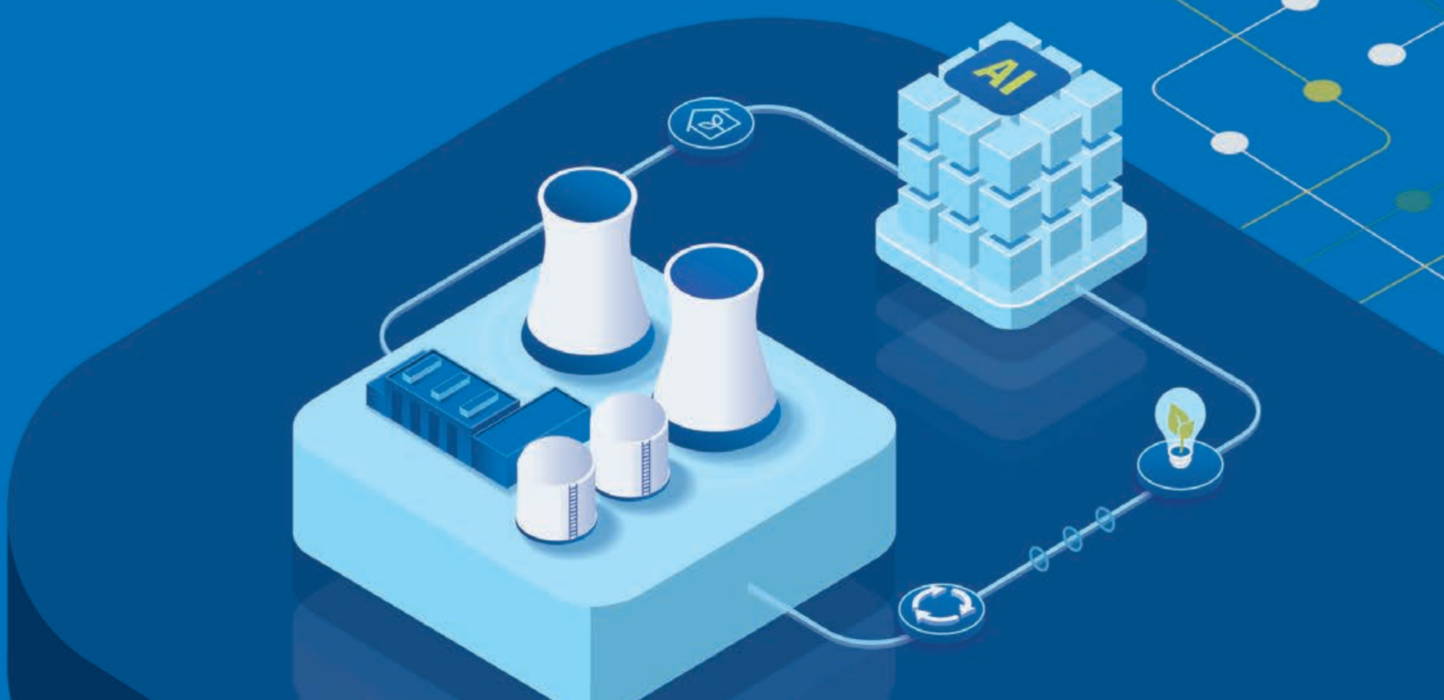
FIG. G.1. Top image: JET interior with superimposed plasma. The insert shows the temperature footprint of the wall components. (Source: EUROfusion)

Bottom image: (Left) Fusion reactions in the plasma core and other plasma processes, depending on the temperature and fuel density. Molecular species can form near to the reactor wall, where the plasma is cooler; (Centre) Plasma-surface interactions take place at the reactor first wall;

(Right) Energetic plasma particles, such as neutrons and ions, may penetrate deep into reactor components, leading to extended material damage. (Source: IAEA)

H.

Application of Artificial Intelligence (AI) in Nuclear Power and the Nuclear Fuel Cycle



H. Application of Artificial Intelligence (AI) in Nuclear Power and the Nuclear Fuel Cycle

Status

Machine learning and artificial intelligence (AI) techniques are increasingly applied to improve quality and efficiency in the nuclear industry. As part of the nuclear fuel assembly manufacturing process at ENUSA, Spain, the surface of UO2 pellets is visually inspected at the end of their ceramic production process, to ensure that they fulfil quality requirements. An image of the lateral surface is obtained using a camera and is automatically analysed by software. This is a more robust method than visual inspection, as it avoids variability due to human factors like subjectivity or fatigue. In the Russian Federation, automatic control of the appearance of fuel pellets is carried out at the fabrication plants of TVEL Fuel Company. Novosibirsk Chemical Concentrates Plant has developed and integrated into its production line a number of systems for quality control of fuel assembly's components.

The US Electric Power Research Institute is currently investigating the possible use of AI to analyse pictures taken during remote inspections of loaded spent fuel storage canisters to ensure uniformity and eliminate human factors in evaluating possible findings like discolorations, scratches or pitting.

Trends

In 2024, AI continued to be applied to commercial nuclear power and nuclear fuel cycle facility design and operation. These applications may improve safety, operational efficiency and cost-effectiveness while also facilitating the development of advanced nuclear technologies. AI-based systems are being introduced in the context of other trends, such as increased digitalization and the adoption of robotic and drone-based systems at operating NPPs. The use of AI in advanced manufacturing enables increased efficiency, flexibility and customization in production processes while also driving down costs and improving quality. These advancements contribute to the sustainability and competitiveness of nuclear energy in the modern energy landscape.

AI is employed in various ways to enhance performance, reliability, security, safety, efficiency and cost-effectiveness in the nuclear industry. The intelligent or smart plant concept, integrating advanced digital technologies and AI applications across a broad range of NPP operation and maintenance processes to improve efficiency and enhance reliability, is being deployed in China, the Republic of Korea and elsewhere. Also, AI-based systems are supporting the project management and oversight of new NPP projects in China.

AI is applied to optimizing reactor core designs. AI-driven solutions optimize fuel loading patterns and extend fuel load duration. This could increase power output, while minimizing waste production and reducing operational costs. Additionally, AI is increasingly supporting advanced nuclear reactor and fuel cycle facility design 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 continue accelerating as experience accumulates and uncertainties are addressed. The use of AI methods in the nuclear industry does not exclude human participation, but simplifies and optimizes human work, reducing the influence of the human factor on results. At the same time, the final decisions should still be made by a human, taking into account the results obtained using AI methods.

I. Human Health

I.
Human Health

I.1.
Enhancing Radiotherapy Efficacy through Novel Approaches
Status

Status

Cancer remains a leading cause of death worldwide, claiming 9.74 million lives and resulting in 19.98 million new cases in 2022. Despite nearly half of all cancer patients requiring radiotherapy at some point, access to this life-saving treatment is limited.

To address this, the Agency led a Lancet Oncology Commission on Radiotherapy and Theranostics, comprising leading experts from 44 academic institutions and medical centres in 23 different countries, to examine radiotherapy availability. Lancet Oncology Commissions not only tackle the most pressing issues in cancer care but also provide policy and practice-changing recommendations.

The Commission found that the disparity in equipment availability remains a challenge, with low-income countries on average needing more than eight times their current number of machines just to meet the target of one machine per 500 patients. In these settings, one teletherapy machine serves more than 15.6 million people, whereas in high-income countries, the ratio is 1 per 130 000 people. Regarding human resources, the 2022 workforce would need to increase by more than 60% to meet the projected global burden of 35.3 million new cases and 18.5 million deaths in 2050.

FIG. I.1., IAEA DG Rafael Mariano GROSSI and HE Mr. Abdulhamid Alkhalifa, President of the OPEC Fund for International Development during their visit to the IAEA Dosimetry laboratory, together with Deputy Director General, of the Nuclear Science and Applications Department Ms. Najat Mokhtar. (Source: IAEA)

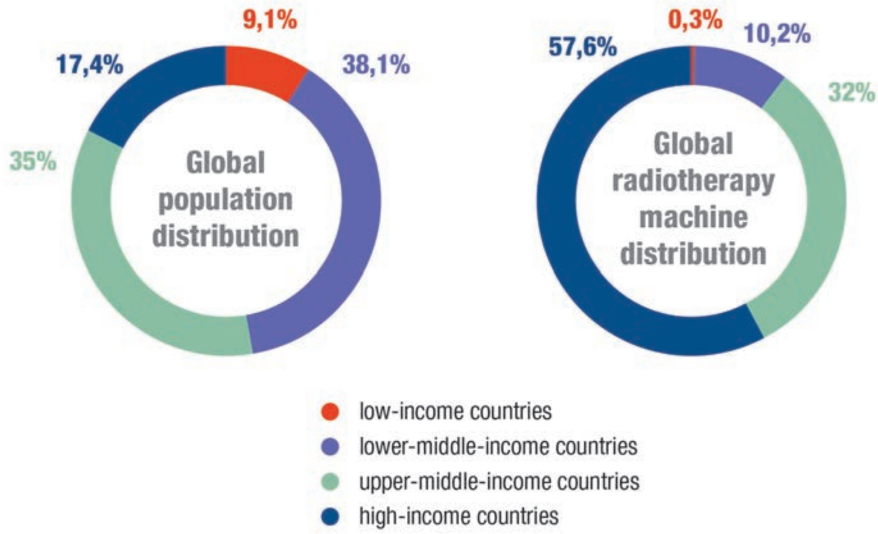


FIG. I.2. Global access to radiotherapy treatment for cancer patients, (Graphic: IAEA)

In light of recent and rapid advances in radiopharmaceutical therapies beyond traditional radiotherapy, the Commission also addresses access to theranostics — the combination of therapeutics and diagnostics. Like traditional radiotherapy, theranostics requires knowledge of radiation principles and radiation biology, as well as expertise in imaging technologies and radiopharmaceutical usage. Despite theranostics showing transformative potential, the Commission found that supply chains, workforce, and regulatory challenges all affect the use of radiopharmaceutical therapies. Iodine-131, which has been part of the standard of care for hyperthyroidism and thyroid cancer, was the exception as the most used radionuclide treatment globally.

Trends

To enhance access to life-saving cancer treatments, the Agency-led Lancet Oncology Commission investigates mitigating initiatives such as workflow optimization, resource-sparing approaches, and advanced techniques. For examples, implementing hypofractionation — fewer but higher doses of radiation per daily treatment session over a shorter time frame — can extend access to an additional 0.8 million prostate cancer patients and 1.4 million breast cancer patients using existing resources. A 50% substitution of conventional radiotherapy with hypo fractionated radiotherapy can yield cost savings of US $1.28 billion and US $1.48 billion, respectively.

Investing in advanced treatments, such as stereotactic body radiation therapy (SBRT) — a form of hypofractionation delivering precise, high doses but requiring upfront investment in advanced equipment — can also result in long-term cost savings, even in low- and middle-income countries (LMICs). Through health economics modelling, the Commission demonstrated this in Mongolia for lung cancer. Similarly, modelling of theranostics treatment for prostate cancer ([177Lu]PMSA) showed a total social impact of $725 million over seven years across nine countries representative high-, upper middle-, and lower middle-income economies.

FIG I.3. IAEA Director General Rafael Mariano Grossi and Korea Institute of Radiological and Medical Sciences (KIRAMS) President Jin Kyung Lee during the Rays of Hope (RoH) Anchor Centre signing ceremony. (Photo: KIRAMS)

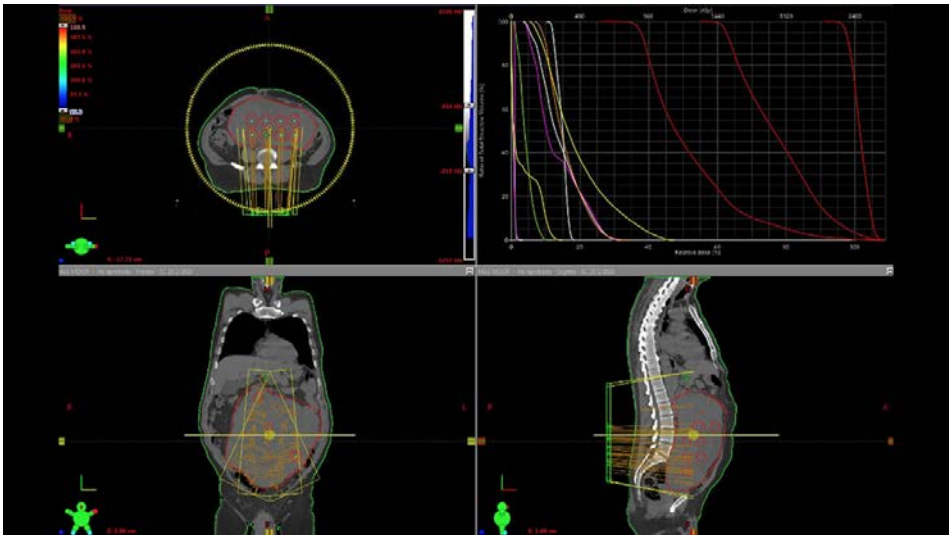


FIG. I.4. A bulky abdominal-pelvic metastatic tumour being irradiated using the lattice technique. The red spheres represent high radiation doses that directly kill tumour cells, while the surrounding areas receive lower doses, provoking an immunological response in the tumour and stimulating further destruction. (Photo: Dr Rolando Loria, Radiotherapy Department, Hospital México, San Jose, Costa Rica. (Image courtesy of Naipy Perez, Innovative Cancer Institute, Miami, USA)

The IAEA's Rays of Hope initiative helps Member States to expand global access to radiotherapy. As of December 2024, the Agency has established a total of 11 Anchor Centres — knowledge and capacity building hubs that serve as vehicles for cancer care collaboration and cooperation on education, training, quality assurance, innovation and research.

The Agency is also conducting research on spatially fractionated radiation therapy (SFRT), an innovative technique to treating large and radioresistant tumours by delivering non-uniform radiation doses across tumour volumes. This approach allows for safe dose escalation to enhance tumour control and improve patients' quality of life through pain relief. Techniques include: (i) GRID therapy: uses physical or virtual grids to create high-dose regions interspersed with low-dose areas, stimulating immune response and promoting tumour shrinkage; (ii) lattice radiation therapy: utilizes photon-based volumetric modulated radiotherapy (VMAT) to safely and effectively treat large, deep-seated tumours; and (iii) SBRT-PATHY: delivered using VMAT, it leverages non-targeted effects of radiotherapy, including bystander and abscopal effects.

While SFRT has shown promise in treating bulky tumours such as sarcomas, lung cancer, and head and neck cancers, further clinical trials are needed to define its role in clinical setting. Establishing consensus on dose prescription and technical administration is essential to validate SFRT.

The Agency initiated a coordinated research project in April 2020 to assess SFRT's efficacy and feasibility in improving clinical outcomes for patients with advanced cervical and lung cancer in LMICs. The project is bringing together 15 Member States across five geographic regions to conduct this research.

■ J.
Food and Agriculture

J. Food and Agriculture

J.1. Enhancing Food Safety Standard Setting through Innovative Radiolabelling of Veterinary Pharmaceuticals

Status

Safeguarding consumers from potentially harmful agrochemicals, such as veterinary drugs and pesticides, and facilitating fair global trade requires harmonized standards such as the Codex Alimentarius maximum residue limits (MRLs). Establishing these standards requires data on how these chemicals are absorbed, distributed, metabolized and excreted in food animals. With this information, it is possible to determine the withdrawal period during which food products are safe for consumption after the last administration of the drugs.

This process requires the use of radiolabelled drugs, with MRLs serving as a reference for applications such as the World Trade Organization Agreement on Sanitary and Phytosanitary Measures during trade disputes and standards set by the World Organisation for Animal Health.

Trends

Limitations in research and development capabilities to generate MRL-related data were identified in many Member States. To address this gap, the Agency initiated a coordinated research project (CRP) entitled “Depletion of Veterinary Pharmaceuticals and Radiometric Analysis of their Residues in Animal Matrices”, through which research is conducted on a wide range of drugs and food animals

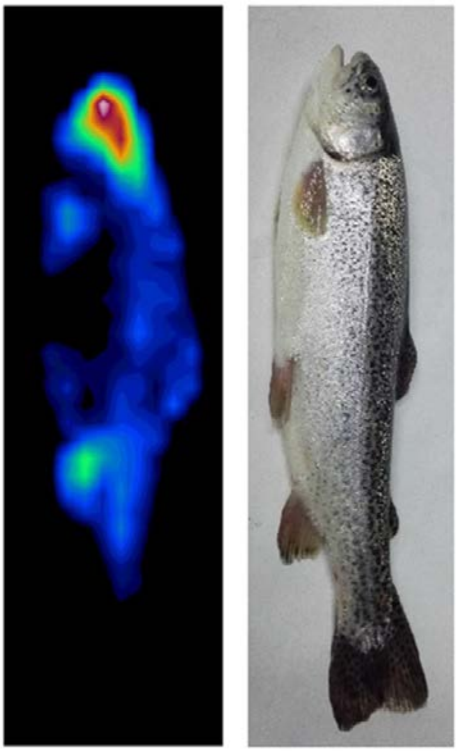


FIG. J.1. Fish treated with zinc-65 radiolabelled drug and visualized through imaging. (Photo: IAEA) including fish, poultry, sheep and goats. While this type of work typically involves the use of radioisotopes such as carbon-14 and hydrogen-3, the CRP explored the use of other radioisotopes such as zinc-65, which forms stable complexes with the substances to be labelled and has a half-life that is shorter (244 days) but still long enough to facilitate depletion studies. The use of this nuclear technology offers solutions to the challenge of high-cost radioisotope purchases and export as well as delivery mechanisms.

The CRP also empowers Member States to be actively involved in the process of generating scientific data for national or global food safety standards. Through such research initiatives, Member States could now consider using existing infrastructure, such as cyclotrons, not only to produce radioisotopes for human radiotherapy but also to support research on food animals enhancing food safety systems in the country.

J.2. Efficient Food Fraud Detection

Status

Many foods have added value because of their strong regional or national identity, often resulting in the food receiving a ‘geographical indication’ (GI). This status incentivizes the economically motivated adulteration or complete substitution of the GI food with a counterfeit product. However, food components such as proteins and sugars carry an inherent origin signal linked to their place of production through stable hydrogen isotopes. Carbon-bound non-exchangeable (CBNE) hydrogen does not interact with outside elements like water, making it useful for detecting food fraud and identifying the geographical origin of food products using a technique called isotope ratio mass spectrometry (IRMS). Scientists can measure stable hydrogen isotope ratios to ensure that food products originate from a particular location. This process, though relatively time-consuming, is made possible because the non-exchangeable hydrogen in plant materials is linked to the water used by the plant during photosynthesis to create tissues such as starch. In turn, the stable hydrogen isotope ratios in water exhibit a systematic global distribution related to geographical origin. This water signal locked in the plant tissue is the ‘fingerprint’ that links the plant to its growing location and any added value claims on food related to specific countries or regions (e.g., Jamaican Blue Mountain coffee, Sri Lankan tea, Thai jasmine rice, and Parmigiano Reggiano cheese).

Trends

The Agency has developed the first in a series of innovative methods using an elemental analyser combined with IRMS (EA-IRMS). The research behind ‘*food authentication by synthetic transformations combined with isotope ratio mass spectrometry (FAST-IRMS)’* introduces a faster and more accessible way to check the authenticity of foods.

This method is especially useful for quickly analysing the non-exchangeable hydrogen from sugars in foods and beverages to detect any hidden addition of cheap sugar syrup products in adulterated products. The method also provides information about the geographical origin of food.

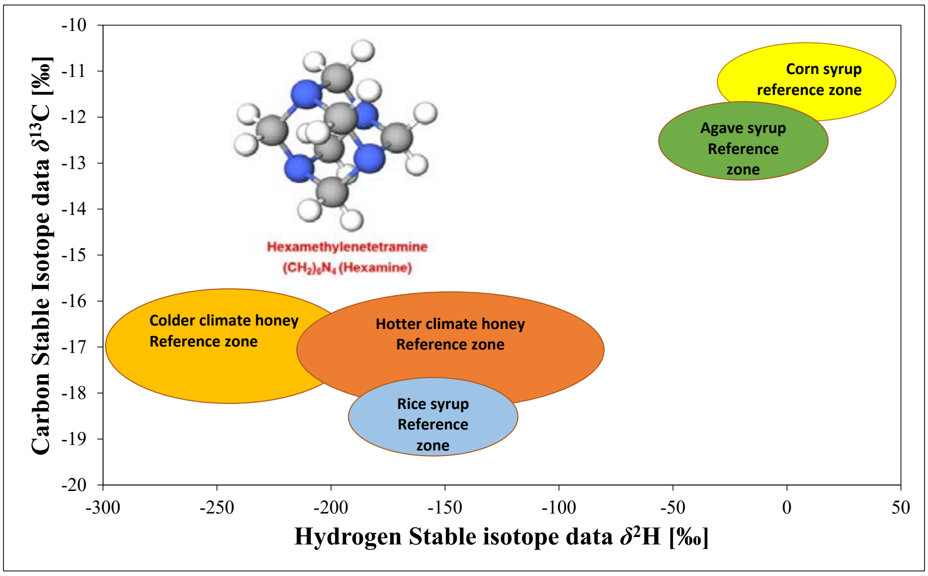


Fig. J.2: A graph showing samples of genuine honey from Canada, New Zealand (in the colder climate amber reference zone) and Malaysia and Vietnam (in the hotter climate orange reference zone), which can be clearly distinguished from cheap sugar syrups made from rice, corn and agave (blue, yellow and green reference zones, respectively). This new method enables Members States to rapidly detect economically motivated adulteration of premium honeys with cheap sugar syrups using hydrogen and carbon stable isotope analysis of the sugars after they have been converted to "hexamine". (Image courtesy of Simon Kelly, formerly Joint FAO/IAEA Centre).

This approach offers several key benefits:

- Faster results: Reduces the time needed compared to traditional methods.
- Better accuracy: Avoids hydrogen exchange issues, leading to more reliable results.
- Wider accessibility: Allows more laboratories worldwide to benefit from advanced testing using EA-IRMS systems without requiring expensive equipment.

Overall, the FAST-IRMS method enables countries and laboratories to detect food fraud efficiently, ensuring the authenticity of added-value food products.

J.3. Rapid Disease Detection and Diagnostic Methods to Tackle Banana Fusarium Wilt TR4

Status

Early detection of plant pathogens is crucial to curtail the spread of diseases and minimize crop damage. For effective prevention and control, early diagnostics are essential to mitigate further spread and impact.

The detection of the banana Fusarium wilt pathogen, *Fusarium oxysporum* f. sp. *cubense* (*Foc*) tropical race 4 (TR4), remains critical due to its severe impact on global banana production, particularly in regions vulnerable to climate change. While molecular diagnostic techniques such as polymerase chain reaction (PCR), quantitative PCR (qPCR), and loop-mediated isothermal amplification (LAMP) are widely used, limitations in sensitivity and field applications require rapid and reliable point-of-care detection tools. These tools minimize the lag between sampling and diagnosis, improving containment of *Foc* TR4's transboundary movement.

The Agency, through the Plant Breeding and Genetics Laboratory (PBGL), has developed a novel method exhibiting exceptional sensitivity, specificity, and reproducibility, making it a strong candidate for point-of-care detection in farmers' fields. Originally tested for detecting *Foc* TR4, the method demonstrated portability, ultra-sensitivity, specificity and cost-effectiveness. It was successfully validated across several isolates, supporting the accurate and early detection of pathogenic strains. This assay enhances diagnostic speed and reliability, reducing the resources needed for containment procedures. Combining mutation breeding with rapid diagnostic tools provides a comprehensive approach to crop protection and production.

Trends

There is a growing trend toward integrating nuclear techniques, such as mutation breeding, with biotechnologies for disease detection as a holistic management strategy. This approach is becoming increasingly important as climate change drives unprecedented pathogen incidences. These shifts align with global climate models that predict a rise in plant pathogen incidents, necessitating quicker and more accurate diagnostic responses.

The Agency, through the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, has pioneered advanced fit-for-purpose diagnostics assays for *Foc* TR4 detection using the DNA endonuclease-targeted CRISPR trans reporter (DETECTR) system. These highly sensitive assays, validated across several pathogen isolates, allow for the specific detection of *Foc* TR4 using a panel of related races, strains, endophytes and other relevant species. They are suitable for point-of-care diagnostic applications, supporting early intervention at primary points of entry while offering sustainable and cost-effective management.

FIG. J.3. IAEA Director General Rafael Mariano Grossi visiting the Plant Breeding and Genetics Laboratory in Seibersdorf. (Source: IAEA)

FIG. J.4. Internal symptoms of Fusarium wilt caused by Foc TR4. Browning of xylem tissues in susceptible banana mutant lines contrasted with no browning in resistant mutants. (Source: IAEA)

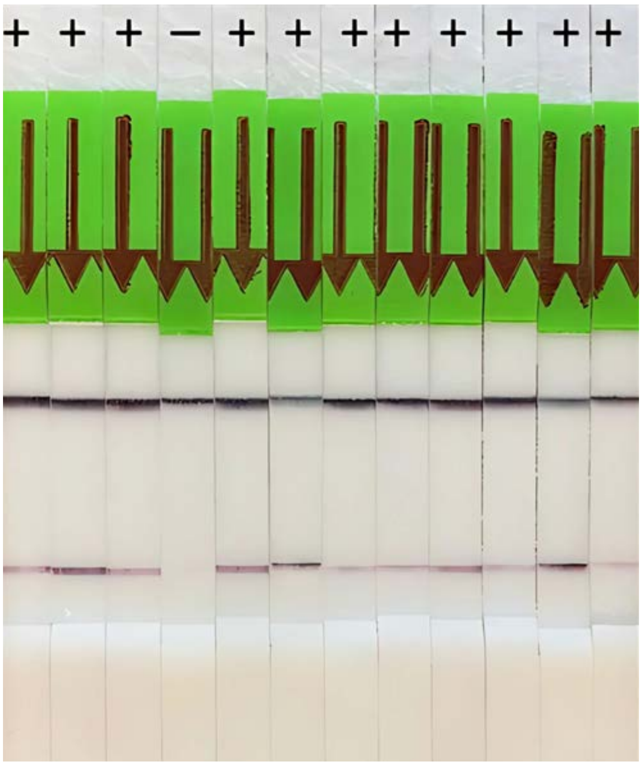


FIG. J.5. CRISPR/CAS-based Foc TR4 DETECTR screening of banana mutants. '–' and '+' indicate resistant and susceptible plants, respectively. (Source: IAEA)

This technology is rapid, reliable, and resource-efficient, requiring no sophisticated laboratory setup, minimal sample preparation, and limited operator training. Efforts are ongoing to integrate this technology with biosensors, further improving detection capabilities for *Foc* TR4 at minimal pathogen levels.

Through training programmes, the Agency is building the capacities of Member States to utilize cutting-edge detection tools and techniques. These efforts complement resistance-based breeding pipelines, proactively improving resilience to *Foc* TR4 in bananas through science-based interventions.

K.
Radioisotope and Radiation Technology

K. Radioisotope and Radiation Technology

K.1. Unlocking Potential: Electron Beam Systems for Global Applications

Status

Ionizing radiation can interact with the molecular bonds altering the physical, chemical, and biological properties of materials, making it an essential tool in industry, medicine, waste management and scientific research. Irradiation facilities in Member States play a significant role in the achievement of Sustainable Development Goals, as well as supporting Agency initiatives such as NUTEC Plastics and Atoms4Food.

Electron beam technology, increasingly popular, is currently used for industrial purposes in 40 Member States. Many governments and international organizations advocate for and support the adoption of alternative technologies, such as electron beams and X-rays, over industrial radioactive sources where feasible. These alternatives offer key advantages, including on-demand operation for safety and reduced security risks.

FIG. K.1. Director General Rafael Mariano Grossi attending the Joint Annual Consultancy Meeting with Collaborating Centers in the field of Radiation Technologies highlighting the importance of advancing radiation technologies for sustainable development and environmental global benefit. This collaborative effort is strongly connected with IAEA Flagship initiatives such as NUTEC Plastics and Atoms4Food, but also in another strategic activities likewise preservation of cultural heritage, Machine-based technologies, Radiotracer techniques for environment mitigation, and Non-destructive Testing for civil engineering and natural disaster management. (Source: IAEA)

Trends

Historically, accelerators were complex and expensive. Recently, however, numerous compact, versatile, and more reliable models have been developed for various applications.

The Agency is bridging gaps in the knowledge and regulatory framework for electron beam technology to address the need for cost-effective and accessible equipment in Member States. This approach not only enhances understanding of the technology but also supports its widespread implementation through two mechanisms:

- Transportable Electron Beam Accelerator System: A transportable electron beam accelerator system will be installed at the Agency's laboratories in Seibersdorf, along with a well-equipped laboratory, by the end of 2025. This system will support training and pilot operations, helping users understand the technology and its applications, such as polymer modification and environmental solutions. Facilitating access to this technology will enhance understanding of regulatory aspects and encourage broader acceptance amongst Member States, leading to the informed adoption of this advanced approach (Figure K.1).
- Framework and Guidelines for Member States are being developed to assist Member States in acquiring and advancing electron beam technology. (Figure K.2).

FIG. K.2. Model of the transportable electron beam accelerator system to be installed at the Agency's laboratories in Seibersdorf, with support from the Republic of Korea and the USA. Its establishment was officially announced at a side event held on 26 November 2024 during the Agency's Ministerial Conference on Nuclear Science, Technology and Applications and the Technical Cooperation Programme. (Source: IAEA)

FIG. K.3. Electron beams are currently used for industrial purposes in 40 Member States. Here, semiconductors are irradiated with a 10 MeV (20 kW) electron beam system in a private enterprise in Daejeon, Republic of Korea. (Source: IAEA)

K.2. Exploring Non-Destructive Testing in Additive Manufacturing (3D Printing)

Status

Additive manufacturing, with 3D printing as its most widely recognized technology, is revolutionizing industries by enabling the production of intricate geometries, lightweight structures, and highly customized components. Unlike traditional manufacturing methods, which involve removing material (subtractive manufacturing) or casting parts in molds, additive manufacturing builds objects layer by layer, allowing for greater design freedom (Figure K.3). This approach reduces material waste and promotes energy efficiency, making it a more sustainable manufacturing solution. Applications span aerospace, and automotive industries, healthcare, energy and consumer goods, where the ability of additive manufacturing to produce complex, high-performance parts is driving innovation.

Despite its benefits, additive manufacturing faces challenges in ensuring the consistent quality and structural integrity of printed components. The layer-by-layer nature of additive manufacturing can result in unique issues that compromise the performance and safety of the final product. These challenges highlight critical need for robust quality assurance methods to verify the reliability and durability of additive manufacturing components, particularly for safety-critical applications such as aircraft components, medical implants or energy infrastructure.

Non-destructive testing (NDT) plays a crucial role in addressing these challenges by enabling the inspection and evaluation of additive manufacturing parts without causing damage. Unlike destructive testing, which requires the cutting or breaking of parts to analyse their properties, NDT techniques such as X-ray/gamma computed tomography, ultrasonic testing, and laser-based methods assess parts for defects like voids, cracks, and lack of fusion. However, the intricate internal structures and complex geometries common in additive manufacturing pose challenges for traditional NDT methods. Furthermore, the lack of universal standards for applying NDT to additive manufacturing parts is a major obstacle. In conventional manufacturing, NDT methods are well-established and standardized, but additive manufacturing introduces new variables such as unique material properties, anisotropic mechanical behaviour and process-specific defects. This creates a need for tailored NDT approaches and comprehensive testing protocols that are specific to additive manufacturing processes and materials.

Trends

Advanced NDT techniques, such as X-ray and gamma computed tomography, offer significant potential for accurately detecting internal defects in complex, multi-material or uniquely designed 3D-printed structures. However, research into integrating real-time, in-situ monitoring systems into the additive manufacturing process remains limited. These real-time techniques could detect defects during production, reducing reliance on post-production evaluations. Addressing these challenges is essential to fully realize the potential of additive manufacturing and ensure its safe and reliable application across various industries.

To support global efforts in this area, the Agency will launch a CRP to develop advanced nuclear-based NDT and online testing techniques. This initiative aims to improve the quality assurance for printed materials and support safe, reliable applications in the additive manufacturing industry.

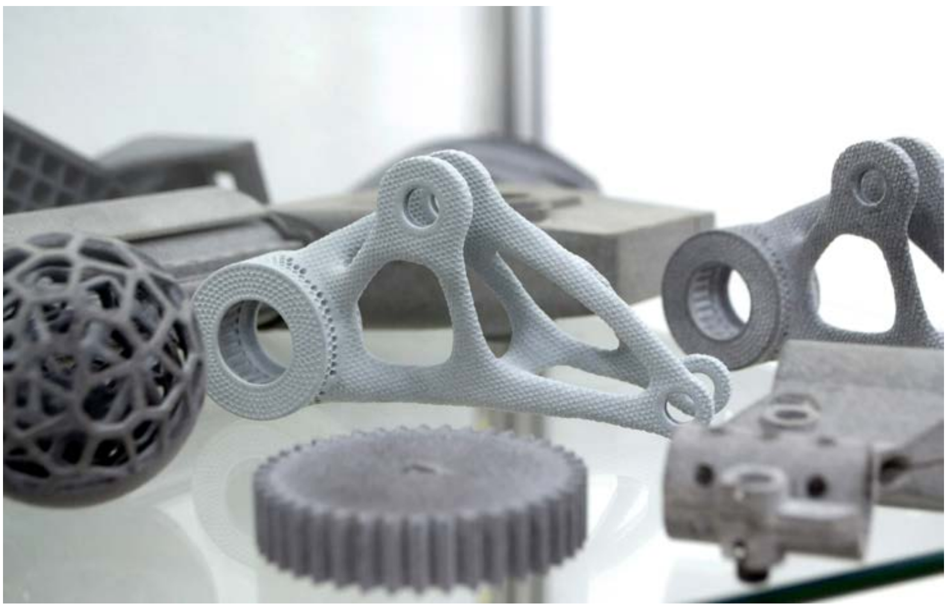


FIG. K.4. Various objects printed using an industrial powder 3D printer. (Photo: AdobeStock)

K.3. Auger Electron Emitters: A Future Trend in Radioligand Therapy

Radioligand therapy (RLT) represents a highly effective treatment option for cancer, particularly in cases where conventional therapies are less effective, such as in the advanced or metastatic stages of the disease.[1] RLT works by utilizing radionuclides that emit beta particles, alpha particles or Auger and/or conversion electrons. These radionuclides are conjugated to selective delivery vectors (such as peptides, antibodies, or antibody fragments) that target the cancerous cells (Figure K.4).). This targeted approach allows RLT to selectively damage or eliminate cancer cells while minimizing the collateral harm to surrounding healthy tissue.[2]

The choice of radiation emitted by a radionuclide for RLT depends on a combination of emission energy and linear energy transfer (LET).[3] Beta particles, which have relatively high energy (in the MeV range) and low LET, penetrate tissue over longer distances (millimetres) before dissipating their energy. In contrast, alpha particles and Auger electrons (AE) have higher LET, meaning that they deposit their energy within close range of the targeted cancer cell. This enables highly localized damage, leading to better selectivity and reduced damage to surrounding healthy cells. Auger electrons, with their lower energy (in the eV–keV range, compared to the higher MeV range of alpha particles), release their energy more precisely within the targeted cell. This positions AE-based RLT as one of the promising and selective therapeutic options currently available. However, it is crucial to choose the right radionuclides and delivery systems to optimize efficacy.

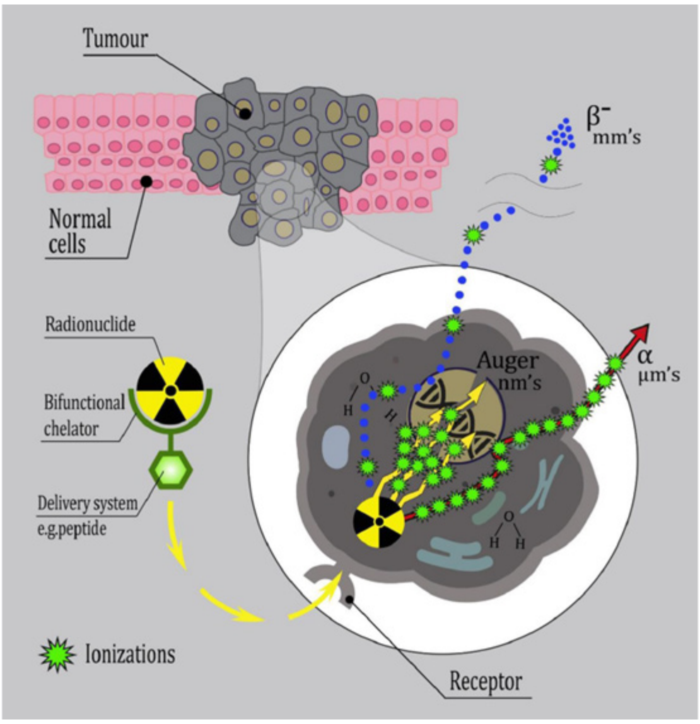


FIG. K.5. Schematic overview of the RLT principle, highlighting the emission of beta, alpha and Auger electrons. (Graphic IAEA)

1 Radchenko, V., & Hoehr, C. (2020). Modern Alchemy to Fight Cancer. Nuclear Physics News, 30(2), 28–32.
2 Sgouros, G., Bodei, L., McDevitt, M.R. et al. Radiopharmaceutical therapy in cancer: clinical advances and challenges. Nat Rev Drug Discov 19, 589–608 (2020).
3 Kassis AI, Adelstein SJ. Radiobiologic principles in radionuclide therapy. J Nucl Med. 2005 Jan; 46 Suppl 1: 4S-12S. PMID: 15653646.

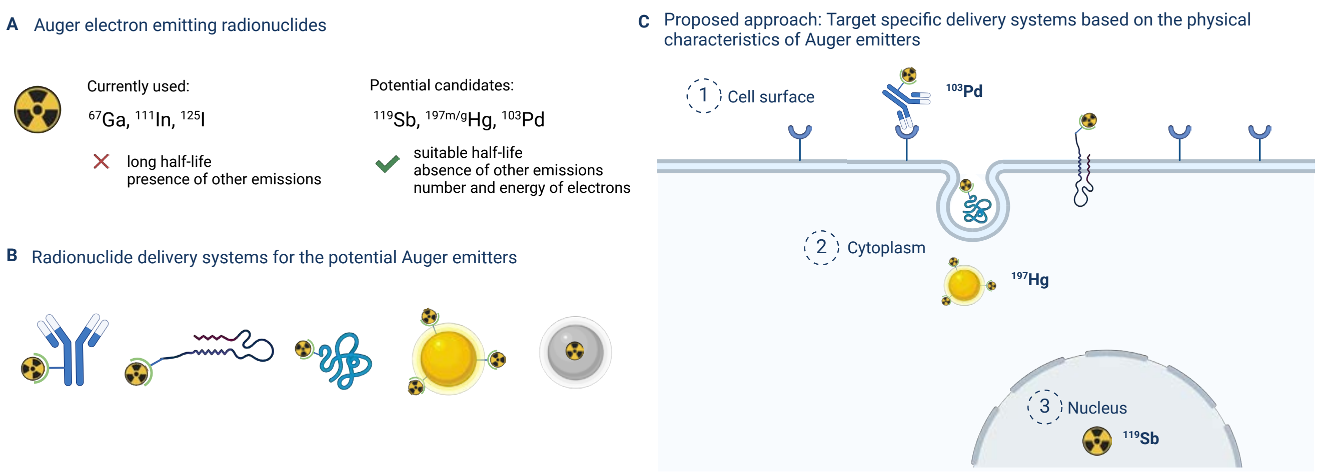


FIG. K.6. (A) Overview of currently used AE-emitting radionuclides and potential candidates for future AE-based RLT applications. (B) Rational design of delivery systems for AE emitters, including antibodies, peptides, proteins and inorganic nanoparticles. (C) Optimal strategies for delivering Auger emitters to targeted sites using delivery vehicles that match the physical characteristics of the emitters, such as half-life and electron energy. (Graphic: Gökçe Engüdar via BioRender)

To identify patients who would benefit the most from RLT, theranostics — the use of diagnostic tools alongside therapeutic agents, based on the same delivery system and medical radionuclides — has become an essential strategy.

Trends

Selecting the most suitable radionuclides for AE-based RLT is critical for the success of radiopharmaceutical development. Key factors in this selection include the radionuclide's half-life, the number of Auger electrons emitted, and any accompanying radiation emissions.[4] Equally important is ensuring that the chosen radionuclides can be produced on a clinical scale. A notable advantage of many potent Auger emitters is that they can be produced using conventional medical cyclotrons, making them widely accessible worldwide.[5]

Currently, most research into AE-based RLT is based on commercially available radionuclides such as indium-111 and iodine-125, which may not be the optimal candidates. Consequently, significant effort is needed to develop production technologies capable of generating the ideal radionuclides for AE-based RLT (Figure K.6).

The selection of the most suitable radionuclides for AE-based RLT must be approached within the broader context of radiopharmaceutical design.[6] This includes matching the radionuclide with an appropriate delivery system that ensures internalization into the target cell's cytoplasm or close proximity to the cell's nucleus. Additionally, the use of a suitable chelator is often essential for attaching the radionuclide. To this end, a group of experts in radionuclide production, radiochemistry, radiolabelling and radiobiology convened at an

4 Filosofov D, Kurakina E, Radchenko V. Potent candidates for Targeted Auger Therapy: Production and radiochemical considerations. Nucl Med Biol. 2021; 94-95:1-19. doi: 10.1016/j.nucmedbio.2020.12.001.
5 Cyclotrons used for Radionuclide Production, IAEA Accelerator Knowledge Portal, https://nucleus.iaea.org/sites/accelerators/Pages/Cyclotron.aspx
6 Ku, A., Facca, V.J., Cai, Z. et al. Auger electrons for cancer therapy – a review. EJNMMI radiopharm. chem. 4, 27 (2019).

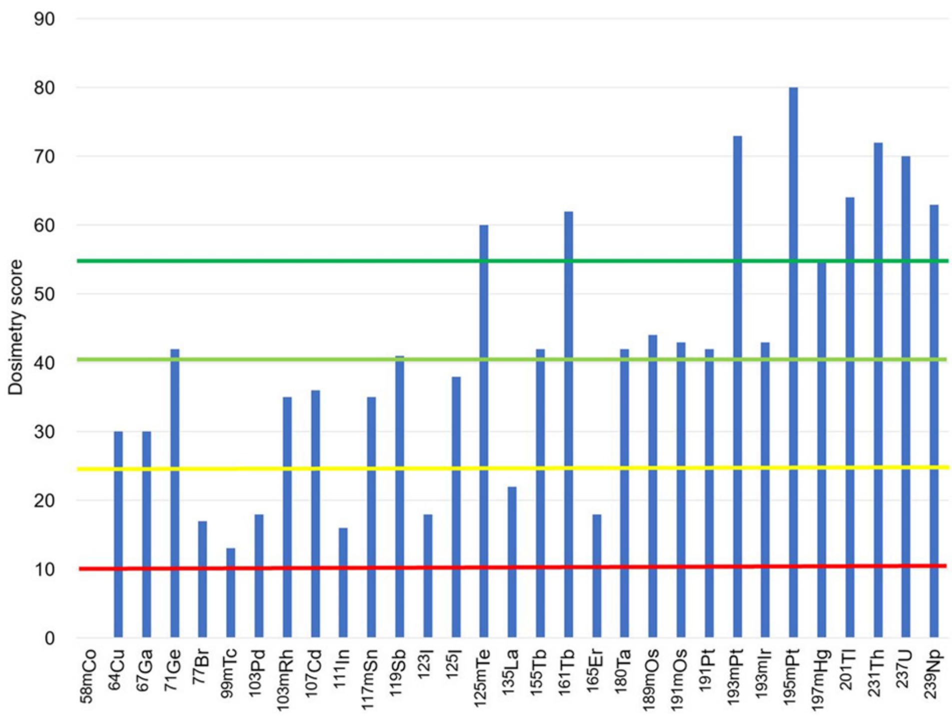


FIG. K.7. Dosimetry scores for the most promising radionuclides for AE-based RLT, as determined through the Agency Technical Meeting in 2022. (Graphic: Journal of Nuclear Medicine Sep 2023, 64 (9) 1344-1351; DOI: 10.2967/jnumed.122.265039)

Agency technical meeting in 2022, where they identified a shortlist of promising radionuclides for AE-based RLT and associated delivery systems (Figure K.7).[7]

The ongoing collaboration among researchers specialising in radionuclide production, radiochemistry, radiolabelling and chelator development, alongside pre-clinical and clinical evaluation, will be pivotal in advancing the development of clinically relevant radiopharmaceuticals for AE-based RLT. The Agency plays a crucial role in facilitating these efforts, providing a platform for technical meetings and coordinated research projects aimed at advancing the next generation of RLT treatments.

K.4. Biobased Polymers for Tackling Plastic Pollution

Status

Materials derived from renewable biological sources, also known as biomass, have garnered significant interest in recent decades due to growing concerns over the depletion of fossil fuel supplies and the environmental impact of synthetic plastics deriving from petroleum sources. This attention has driven the development of methods to convert biomass into valuable compounds or bio-based materials. To improve yield and selectivity, effective biomass fractionation is essential. Most of the conventional methods typically rely on thermochemical processes, using steam or electrical heating, which are often energy-inefficient, leading to prolonged reaction times and the generation of multiple by-products.

7 Bolcaen J, Gizawy MA, Terry SYA, Paulo A, Cornelissen B, Korde A, Engle J, Radchenko V, Howell RW. Marshalling the Potential of Auger Electron Radiopharmaceutical Therapy. J Nucl Med. 2023 Sep;64(9):1344-1351. doi: 10.2967/jnumed.122.265039.

In contrast, the application of ionizing radiation (such as gamma rays and electron beam irradiation) offers a promising solution by maximizing energy efficiency and minimizing unwanted side reactions during biomass pretreatment. Additionally, advances in material science have led to bio-based materials with enhanced mechanical properties, improved biodegradability or recyclability, and cost-competitiveness at an industrial scale.

By taking advantage of biomass as renewable feedstocks (Figure K.7), natural residues such as starch, cellulose, and lignin can be harnessed and irradiated, creating viable alternatives to conventional plastics and reducing reliance on fossil fuels as industries adopt bio-based materials in packaging, agriculture and consumer goods.

Trends

As consumers become more environmentally conscious, there is rising demand for sustainable products. This trend is pushing manufacturers to explore bio-based options, including those derived from the ionizing radiation processing of biomass, to meet market needs for sustainable packaging and products (Figure K.8). As the use of ionizing radiation for the production of bioplastics and the integration of bio-based materials into high-value products expand, there is a growing emphasis on enhancing regulatory frameworks and safety standards. Analytical control of the biobased component in plastics, through C-14 content analysis, can further support regulatory oversight and enhance consumer information.

By leveraging ionizing radiation techniques, the production of bio-based polymers from biomass not only addresses plastic pollution but also promotes environmental sustainability. There is a trend towards greater collaboration among academia, industry and government to advance research and development in bioplastics, facilitating knowledge transfer and resource sharing.

FIG. K.8. Under Agency activities, different types of renewable feedstock, such as yerba mate waste in Argentina (left) and seaweed in Indonesia (right), are currently being studied to produce sustainable and efficient alternatives to single use plastics. (Photos: Mr Guillermo Arndt: National Institute of Industrial Technology, ARG; Ms Sukna Surya Kusumah: Research Center for Biomass and Bioproducts National Research and Innovation Agency (Source: BRIN))

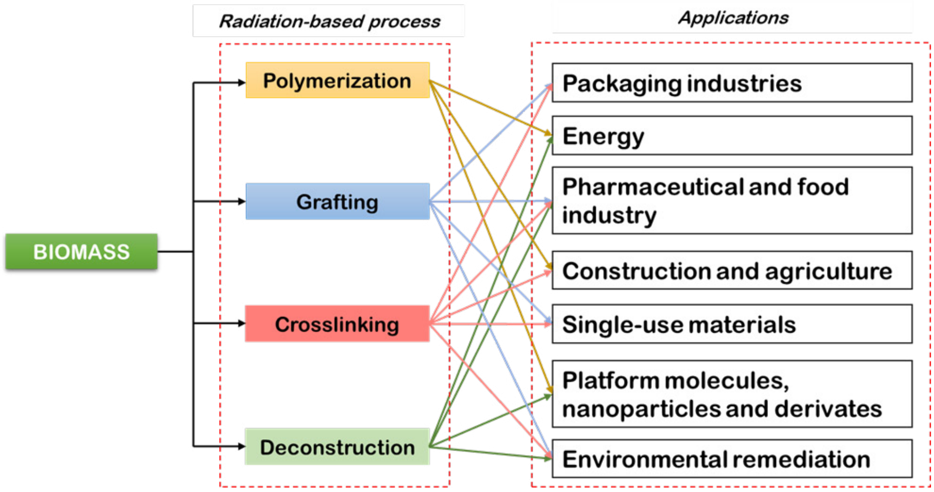


FIG. K.9. Overview of the use of radiation technologies to convert biomass into value added end products. (Graphic: IAEA)

While biobased polymers present promising solutions to plastic pollution, their scalability and integration into existing waste management systems require multidisciplinary approaches. The Agency's involvement through radiation technologies provides unique avenues for innovation and capacity building, helping Member States to develop sustainable alternatives to conventional plastics while addressing global environmental challenges. To help tackle the challenge, institutes from 15 Member States initiated a five-year CRP in 2023.[8] This project also involves local packaging material and food container producers, aiming to develop fully biodegradable seaweed-based bioplastics as an alternative to single-use plastics for retail, e-commerce and residential use.

8 Strengthening the Use of Biomass for Synthesis of Bioplastics and Other Compounds, Using Radiation Technology, www.iaea.org/projects/crp/f22081

L.
Isotope Hydrology

L. Isotope Hydrology

L.1. Fast-Tracking Groundwater

Status

Around half the world's population depends partly or entirely on groundwater for survival, but climate and land use change are threatening the sustainability of this resource. Extreme weather events, such as cyclones and hurricanes, along with changes in ground vegetation cover, are increasing the risk of groundwater contamination by enhancing the likelihood of contaminants migrating from the surface to aquifers. The Agency has been investigating these types of rapid processes through the development of innovative analytical methods for short-lived radionuclides, in particular sulphur-35.

Sulphur-35 is a cosmogenic isotope produced by cosmic ray interaction with argon-40 atoms naturally present in the atmosphere. Sulphur-35 has a half-life of 87.4 days, meaning that it can be used very effectively to look at water reaching aquifers within 1 year — a time frame that is crucial for removing biological contaminants or informing water resource managers of an immediate contamination risk following natural disasters or industrial accidents. The half-life of this tracer is therefore ideal for scientists and water managers seeking to gain a better understanding of the impacts of extreme weather events and land use changes on groundwater recharge and flow patterns.

Effective management of groundwater in the context of water scarcity and vulnerability to pollution in fast recharging systems requires innovative approaches to monitor rapid water transfers between surface and groundwater

FIG. L.1. IAEA Director General Rafael Mariano Grossi with United Nations Office on Drugs and Crime (UNODC) Executive Director, Director General United Nations Office at Vienna (UNOV) Ms Ghada Waly (left) visiting the isotope hydrology laboratory to learn about the isotope tracers that are used to better understand and manage water resources. The laboratory head Ms Jennifer McKay (right) explaining the method for analysis of organically bound tritium (Source: IAEA) systems. This knowledge is crucial for assessing the safety of water sources, for example in emergency settings such as refugee settlements. Informal settlements often lack adequate sanitation systems, leading to significant pollution risks for groundwater systems that may also serve as drinking water sources. Shallow, fractured or karstic aquifers are further examples of water bodies with rapid recharge times (often less than a year) that can be particularly vulnerable to such contamination. Cholera outbreaks, for instance, have been directly linked to the contamination of such aquifers.

Trends

Despite its potential, sulphur-35 has seen limited use, primarily due to its low abundance and analytical complexity. The Agency has worked on several aspects to improve the applicability of this isotope for Member States. The first improvement was to develop a sampling and shipment procedure to reduce the sample size from over 20 litres to 10 grams and to ensure that samples can be stored without losses. The Agency disseminated the sampling protocol and trained CRP participants in the novel methodology. The second improvement consisted of lowering the detection limit by refining sample preparation and measurement by ultra-low-level liquid scintillation counting, while bearing in mind simplicity and costs to ensure that the method is transferable to laboratories in Member States.

The collection and shipment to the Agency by Member States of preliminary samples is planned for 2025, and samples will be analysed in the Isotope Hydrology Laboratory (IHL). Future steps envisioned include the continued transfer of knowledge to laboratories with ultra-low-level liquid scintillation counter facilities in Member States.

Sulphur-35 has also been applied to assess the suitability of managed aquifer recharge (MAR) sites. MAR is seen as a crucial tool for adapting to climate change. It helps to mitigate the impacts of extreme weather events by capturing

FIG. L.2. Collection and concentration of sulphur-35 in the field from groundwater samples using portable resin columns. (Photo: IAEA)

FIG. L.3. Agency interns Daniela Machado and Stephen Wangari preparing water samples for analysis of sulphur-35 in the IHL. (Source: IAEA)

excess water during wet periods and storing it for use during dry periods. MAR projects are increasingly being implemented in Member States, particularly in water stressed regions. These projects are tailored to address specific local challenges, such as salinization in coastal areas and declining water tables in agricultural regions.

The wider use of sulphur-35 will allow for a more detailed and timely understanding of the changes occurring in groundwater systems globally. This is particularly important as the frequency and intensity of extreme weather events continue to rise due to climate change. By tracking fast water transfers, these tracers help in identifying and mitigating contamination risks more effectively.

As global temperatures rise, both surface evaporation and the atmosphere's capacity to hold water vapour will increase. This process dries out soils, lowering moisture levels in seas, lakes and aquifers. When the moisture-laden atmosphere eventually releases rain, it often falls in intense, rapid storms rather than as prolonged, soaking rain. Such storms are more likely to cause flash floods but can also result in rapid recharge of aquifer systems that are being pumped dry.

The inclusion of short-lived radionuclides such as sulphur-35 into the isotope toolkit for groundwater management is an important step forward in understanding the global changes affecting groundwater systems. This initiative aligns with the Agency's commitment to achieving Sustainable Development Goal (SDG) 6 "Clean Water and Sanitation." By integrating these methods into water resources management strategies, the Agency aims to enhance the sustainability and safety of groundwater resources in Member States.

■ M.
Marine Environment

M. Marine Environment

M.1. Evaluating the Impact of Ocean Acidification on Seafood: A Global Approach

Status

As the ocean absorbs carbon dioxide released into the atmosphere from human activities, its carbonate chemistry is altered, leading to ocean acidification. A growing number of studies indicate that ocean acidification — both on its own and in combination with other environmental stressors such as warming and pollution — may negatively impact marine organisms. The IAEA Marine Environment Laboratories in Monaco develop and use nuclear and isotopic techniques to investigate these effects.

Ocean acidification could have severe consequences for nations that are heavily dependent on marine resources, threatening food security, population health, and economic stability. Although ocean acidification is only one of the many factors that can affect seafood sustainability, it has significant potential to disrupt aquaculture industries globally.

Global concern about these impacts on socioeconomically important seafood is increasing worldwide, and the issue of ocean acidification has become an integral part of the United Nations 2030 Agenda for Sustainable Development. SDG 14.3 seeks to “minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels”. It is also an integral part of the new Kunming-Montreal Global Biodiversity Framework under the Convention on Biological Diversity.

Trends

Despite growing evidence of ocean acidification’s harmful effects on marine organisms and ecosystems, there remains a lack of data on seafood species that are socioeconomically critical, particularly in developing countries. Although

FIG. M.1. IAEA Director General Rafael Mariano Grossi, together with IAEA Scientific experts from the Marine Environment Laboratories in Monaco travels to Antarctica to collect samples for analysis under the IAEA’s NUTEC Plastics (NUclear TEChnology for Controlling Plastic Pollution) Initiative. (Source: IAEA) ocean acidification is a global issue, localized studies are needed in order to develop and implement effective adaptation measures and minimize potential negative impacts for vulnerable populations, which can be disproportionately affected.

The CRP entitled “Evaluating the Impact of Ocean Acidification on Seafood — A Global Approach” (2019 to 2023) used standardized experiments to test the effects of potential future ocean acidification conditions on 13 species of shrimp, fish, and molluscs (such as mussels, scallops and abalone). These experiments, which spanned a period of six months, measured a set of commercially relevant parameters such as growth, survival, taste, texture, and other parameters depending on the expertise of their respective laboratories, including changes in metabolism, calcification, and bioaccumulation of chemical contaminants using nuclear and isotopic techniques.

The CRP also tested the ability of species to recover from ocean acidification by reversing the chemical conditions in experimental tanks, offering a potential adaptation strategy for aquaculture. Project participants engaged with local fisheries, aquaculture industries, and the public through awareness activities such as seafood tastings, promoting adaptation and mitigation strategies in their respective countries.

Most project participants had already received basic to advanced trainings in the study of chemical and biological aspects of ocean acidification through the Agency’s Ocean Acidification International Coordination Centre (OA-ICC) and technical cooperation projects. Through this CRP, they had the opportunity to apply their knowledge collaboratively, generating critical data to address the threat of ocean acidification in their respective countries.

FIG. M.2. Researchers from Costa Rica assess the impacts of ocean acidification on the spotted rose snapper (Lutjanus guttatus) as part of the Agency-led CRP. (Photo: University of Costa Rica)

This CRP filled important knowledge gaps regarding the impacts of ocean acidification on seafood while fostering international collaboration and capacity building. The benefits for the participants and their respective countries included enhanced capabilities to conduct marine experimental research and implement best practices for ocean acidification experiments and observations and strengthened national and international collaborations.

This CRP was a first step towards gaining a better understanding of the impacts of ocean acidification on seafood. Moving forward, it will be crucial to continue efforts to address these impacts in the context of environmental variability and multiple stressors, as well as indirect effects that occur through ecological feedback, and to test the implementation of adaptation solutions.

The project provided a unique cooperation platform for research organisations from 14 countries across 5 continents — Africa, Europe, North America, South America and Asia. By co-designing and implementing a comprehensive experimental framework, IAEA has provided important data on species' response to ocean acidification. This was a first-of-its-kind collective assessment of ocean acidification impacts on socioeconomically relevant species, with dynamic knowledge sharing, capacity building and establishment of best practices.

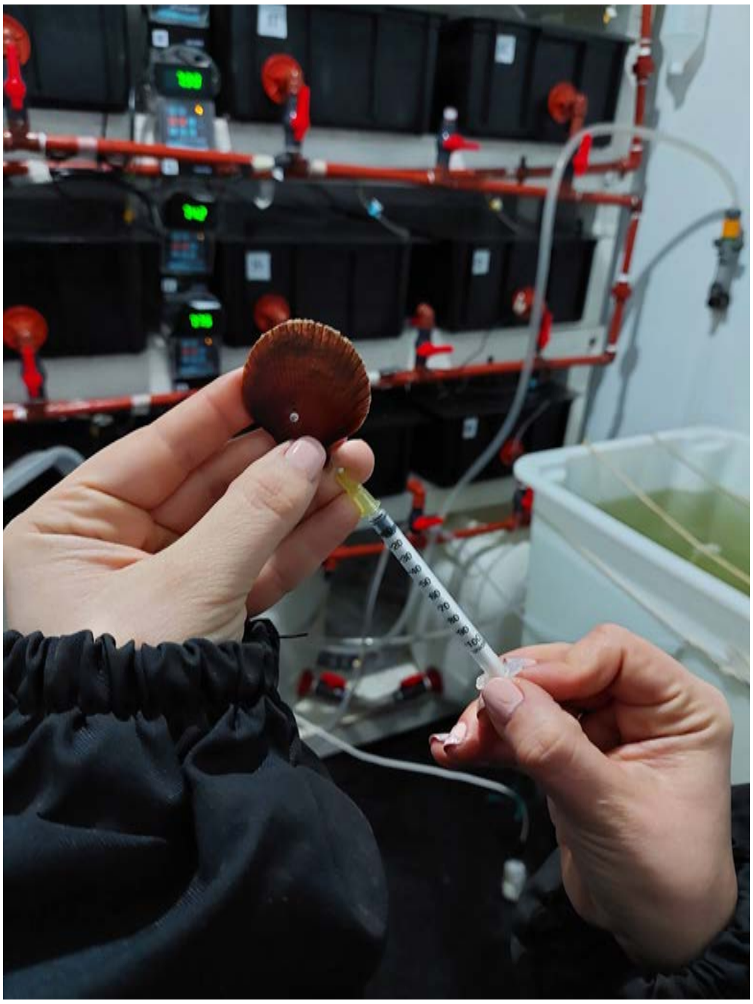


FIG. M.3. A CRP participant from Argentina performs haemolymph extraction on a Patagonian scallop (Zygochlamys patagonica) to assess the effects of ocean acidification on immune response. (Source: Mar Del Plata National University, Argentina)

M.2. Advancing Marine Pollution Insights with Non-traditional Isotope Systems

Status

Isotopes have significantly advanced our understanding of marine pollution and environmental processes. Traditional stable isotopes such as carbon, nitrogen, sulphur, oxygen and hydrogen have long been instrumental in marine research. These isotopes, measured primarily using techniques such as isotope ratio mass spectrometry (IRMS), serve as essential tracers in studying marine chemistry, ocean circulation, biological productivity, contaminant transfer along food chains, and the sources and impacts of pollution. For instance, traditional lead isotopes play a pivotal role in tracking metal pollution in marine environments, helping to assess the effectiveness of environmental regulations aimed at reducing metal contamination. Similarly, the radioactive isotope lead-210 is used to determine sediment ages over a timescale of approximately a century, establishing a chronology of anthropogenic impacts in soils and sediments. When used together, stable and radioactive lead isotopes provide a detailed historical record of lead pollution in a given region, offering valuable insights into its progression over time.

Until recently, the application of stable isotopes was largely limited to light elements such as carbon, nitrogen, hydrogen, oxygen and sulphur, due to challenges in resolving their natural variations. However, advances in instrumentation and analytical methods have broadened the scope to include non-traditional isotopic systems, such as lithium, iron, copper, mercury, and cadmium. The term

FIG. M.4. Sediment core collection in seagrass meadows, north-eastern Brazil. (Source: CIENAM, Federal University of Bahia, Brazil)

FIG. M.5. IAEA Director General Rafael Mariano Grossi, and Jamie Cooke, General Manager Warner Bros. Discovery for Central Europe, Middle East & Türkiye, signs the agreement between the International Atomic Energy Agency and the Discovery Channel at the Agency headquarters in Vienna, Austria. 12 December 2024, in order to further promote the Nuclear Sciences and Applications solutions the IAEA can offer to the Member States. (Source: IAEA)

'non-traditional isotopes' distinguishes these systems from the traditional stable isotopes such as carbon, nitrogen and hydrogen, and radiogenic isotopes such as the uranium–lead system.

The Agency is working to better understand marine environmental processes and pollution using non-traditional isotopes such as zinc, chromium, nickel and copper. These isotopes are gaining prominence in marine research, particularly in areas such as risk assessment, pollution monitoring, and source identification. They help scientists understand how contaminants move through ecosystems. Unlike other analytical methods, which often focus on quantifying total pollutant levels, non-traditional isotopes offer deeper insights into metal dynamics, including their bioavailability, mobility, transport and sources. The application of isotopes such as lithium is particularly noteworthy as these serve as proxies for Earth surface processes such as weathering, erosion, as well as for biological processes such as lithium bioaccumulation. These processes are especially relevant in the context of climate change, which influences the transport and fate of pollutants. By adopting non-traditional isotopic techniques, Member States can enhance their ability to evaluate environmental processes with greater precision. This, in turn, supports the development of more effective pollution mitigation strategies and informs sound ecosystem management decisions.

Trends

In recent years, the study of non-traditional stable isotopes has been transformed by new technologies, in particular the multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). This advanced tool has resolved many previous challenges, allowing scientists to analyse isotopes with greater accuracy and efficiency. These breakthroughs are deepening our understanding

FIG. M.6. Sediment core preparation for radiochemistry analysis. (Photo: CIENAM, Federal University of Bahia, Brazil)

of metal isotope behaviour, which is crucial for tackling issues such as marine pollution and climate change. Combining laboratory experiments with real-world field studies will be key to fully harnessing the potential of isotopic research to address these global challenges.

One promising outcome is the development of new methods to measure isotopes in environments where metals are found in very low concentrations, such as seawater or marine organisms. Such improvements are essential for broadening the applicability of non-traditional isotopes across various research areas. These methods enable scientists to trace the pollutant movement through ecosystems, assess their environmental impacts and explore how climate change may influence these dynamics.

A particular research area of interest focuses on the use of non-traditional isotopes to assess food security and ocean health. By analysing isotopic signatures in marine organisms, researchers can gain insights into environmental conditions, potential pollutant exposure pathways, and associated risks to ecosystem services and human health. These organisms act as proxies for the broader marine environment, providing valuable data on pollution levels and trends.

The integration of isotopic data into studies of marine ecosystems also holds promise for advancing sustainable management practices. By understanding

FIG. M.7. IAEA Director General Rafael Mariano Grossi, at the opening session of the 2024 IAEA Ministerial Conference on Nuclear Science, Technology and Applications and the Technical Cooperation Programme –held at the Agency headquarters in Vienna, Austria. 26 November 2024. The conference brought together key decision makers to review together how nuclear science and technology address global challenges, including climate change, cancer care, food safety, water scarcity and plastic pollution. "For decades, the IAEA has led the way in helping countries harness the great potential of nuclear science and technology," said IAEA Director General Rafael Marino Grossi. "Together we have succeeded in touching the lives of many around the world. But seeing the scale of the challenges, we need to do more." (Source: IAEA)

the pollutant sources and pathways, scientists and policymakers can better target their interventions to mitigate contamination and its effects on marine life.

Future research will likely focus on the development of specific proxies for monitoring environmental processes. For example, zinc and copper isotopes can be used to trace metal transport in aquatic systems, while lithium isotopes provide insights into weathering processes influenced by climate variability. These advances will be instrumental in addressing pressing environmental challenges, including the impacts of climate change on marine ecosystems.

As the demand for sustainable food sources continues to rise, isotopes play an increasingly vital role in ensuring food safety and security. In this context, the Agency's collaboration with Member States becomes even more crucial in effectively addressing these challenges. Marine organisms such as fish and shellfish are integral to human diets but can also accumulate pollutants. Isotopic analysis can help to identify contamination sources, trace pollutant pathways, and assess the risks to human health. This information is crucial for developing strategies to reduce exposure to harmful substances while maintaining the integrity of marine-based food systems. By leveraging these advanced isotopic techniques, Member States are supporting sustainable fisheries and aquaculture, a key part of ensuring the long-term health of marine ecosystems and the communities that depend on them.

■ 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 (2024)	
	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	10.4	7.4
ARMENIA	1	416					2.6	30.8
BANGLADESH					2	2 160		
BELARUS	2	2 220					14.7	36.3
BELGIUM	5	3 908					29.7	42.2
BRAZIL	2	1 884			1	1 340	14.9	2.3
BULGARIA	2	2 006					15.1	41.6
CANADA	17	12 714					81.2	13.4
CHINA	57	55 320			28	29 638	417.5	4.7
CZECH REP.	6	3 963					28.0	40.2
EGYPT					4	4 400		
FINLAND	5	4 369					31.1	39.1
FRANCE	57	63 000					364.4	67.3
HUNGARY	4	1 916					15.2	47.1
INDIA	20	6 920	4	639	7	5 398	49.9	3.3
IRAN, ISL.REP	1	915			1	974	6.4	1.7
JAPAN	14	12 631	19	19 048	2	2 653	84.9	NA
KOREA, REP.OF	26	25 609			2	2 680	179.4	31.5
MEXICO	2	1 552					12.0	4.8
NETHERLANDS, KINGDOM OF THE	1	482					3.4	2.8
PAKISTAN	6	3 262			1	1 117	22.8	16.7
ROMANIA	2	1 300					10.0	19.8
RUSSIA	36	26 802			4	3 850	202.1	17.8
SLOVAKIA	5	2 302			1	440	17.0	60.6
SLOVENIA	1	696					5.6	35.0
SOUTH AFRICA	2	1 854					7.8	3.9
SPAIN	7	7 123					52.1	19.9
SWEDEN	6	7 008					48.7	29.1
SWITZERLAND	4	2 973					23.0	28.6
TÜRKIYE					4	4 456		
UAE	4	5 348					36.5	21.8
UK	9	5 883			2	3 260	37.3	12.3
UKRAINE	15	13 107			2	2 070	NA	NA
USA	94	96 952					781.9	18.2
Worldwide [b]	417	377 014	23	19 687	62	64 461	2 617.3 [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 20 June 2025.

[b] The total figures include the following data from Taiwan, China: 1 unit, 938 MW(e) in operation and 11.7 TW·h of electricity supplied (2024), accounting for 4.6% of the total electricity mix.

c The total electricity production does not include Ukraine as operational data was not submitted for the year 2024.

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	52
Neutron activation analysis	118	51
Radioisotope production	83	41
Neutron radiography	68	35
Material/fuel irradiation	67	26
Neutron scattering	44	28
Geochronology	24	21
Transmutation (silicon doping)	23	14
Transmutation (gemstones)	21	12
Neutron therapy, mainly R&D	17	13
Nuclear data measurement	18	12
Other [c]	117	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 (227 in operation, 7 temporarily shut down, as of December 2024).

[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

AE	Auger electron
AI	artificial intelligence
API	application programming interface
ARAO	Agency for Radwaste Management (Slovenia)
ASIC	application-specific integrated circuit
ASN	Nuclear Safety Authority (France)
ATF	accident tolerant or advanced technology fuel
BWR	boiling water reactor
CEFR	China Experimental Fast Reactor
CLLBC	caesium-lanthanum-lithium-bromo-chloride
COP 28	28th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change
COP 29	29th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change
COVID-19	coronavirus disease 2019
CRP	coordinated research project
CT	computed tomography
DETECTR	DNA endonuclease-targeted CRISPR trans reporter
DEMO	demonstration fusion power plant
DPRAO	Radioactive Waste State Enterprise
EA	elemental analyser
EPC	engineering, procurement and construction
FAO	Food and Agriculture Organization of the United Nations
FAST-IRMS	food authentication by synthetic transformations combined with isotope ratio mass spectrometry
Foc TR4	Fusarium oxysporum f. sp. cubense tropical race 4
GI	geographical indication
GW	gigawatt
GW(e)	gigawatt (electrical)
HALEU	high assay low enriched uranium
HEU	high enriched uranium
HTGR	high temperature gas cooled reactor
HTR-PM	High Temperature Reactor–Pebble-Bed Module
HTS	high temperature superconducting
INIR	Integrated Nuclear Infrastructure Review

INL	Idaho National Laboratory
IRMS	isotope ratio mass spectrometry
JET	Joint European Torus
keV	kiloelectronvolt
LAMP	loop-mediated isothermal amplification
LET	linear energy transfer
LEU	low enriched uranium
LFR	lead cooled fast reactor
LMICs	low and middle income countries
LTO	long term operation
LWGR	light water cooled, graphite moderated reactor
LWR	light water reactor
MAR	managed aquifer recharge
MBIR	Multipurpose Fast Research Reactor
MeV	megaelectronvolt
ML	machine learning
MOX Fuel	mixed oxide fuel
MRL	maximum residue limit
MW(e)	megawatt (electrical)
NDT	Non-destructive testing
NHSI	Nuclear Harmonization and Standardization Initiative
NORM	naturally occurring radioactive material
NPP	nuclear power plant
NTD-Si	neutron transmutation doped silicon
OA-ICC	Ocean Acidification International Coordination Centre
OECD/NEA	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development
ATHY	partial tumour irradiation targeting hypoxic segment
PBGL	Plant Breeding and Genetics Laboratory
PCR	polymerase chain reaction
PFBR	Prototype Fast Breeder Reactor
PMSA	prostate-specific membrane antigen
PRAMU	Uranium Mining Environmental Restoration Project (Argentina)
PWR	pressurized water reactor

PHWR	pressurized heavy water reactor
qPCR	quantitative PCR
R&D	research and development
RLT	radioligand therapy
ROSSPAD system	compact scintillator-based gamma-ray neutron detector for terrestrial and space applications
SABRE	surface access borehole resource extraction
SANS	small angle neutron scattering
SBRT	stereotactic body radiation therapy
SDG	Sustainable Development Goal
SEALER	Swedish Advanced Lead Reactor
SFR	sodium cooled fast reactor
SFRT	spatially fractionated radiation therapy
SMART	system-integrated modular advanced reactor
SMR	small modular reactor
SNF	spent nuclear fuel
SRO	start of research operations
TENMAK	Turkish Energy, Nuclear and Mineral Research Agency
tHM	tonnes of heavy metal
tU	tonnes of uranium
TWh	terawatt hour
UKAEA	United Kingdom Atomic Energy Authority
VMAT	volumetric modulated arc therapy
WCR	water cooled reactor

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