Nuclear Technology Review

■ 2023

Report by the Director General

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

GC(67)/INF/4

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Contents

Summary

- In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* each year. Attached is this year's report, which highlights notable *developments in 2022*.

- The Nuclear Technology Review 2023 covers the following select areas: nuclear power, nuclear fuel cycle, decommissioning, environmental remediation and radioactive waste management, nuclear fusion research and technology development for future energy production, research reactors, particle accelerators and nuclear instrumentation, food and agriculture, radioisotopes and radiation technology, human health, and marine environment.

- The draft version was submitted to the March 2023 session of the Board of Governors in document GOV/2023/3. This final version was prepared in the light of the discussion held during the Board of Governors and also of the comments received by Member States.

Foreword by the Director General

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

In 2022, the convergence of the global climate crisis with turmoil on energy markets brought renewed interest among Member States in the ability of nuclear power to help achieve net zero emissions and ensure energy supply security. At the same time, a growing number of countries use nuclear technologies for non-power applications, including to protect water resources, develop smarter agriculture and save lives through better cancer care.

At the 2022 Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27), held in Sharm El-Sheikh, Egypt, the IAEA oversaw the first-ever pavilion at this event dedicated to showcasing the benefits of nuclear technologies for mitigating climate change as well as monitoring and adapting to its effects. Besides, to further enhance the understanding of the potential of nuclear power in decarbonizing energy beyond electricity, the Atoms4NetZero initiative was launched at COP27. Building on these efforts, the Agency will continue to engage with Member States and the broader international community on the significant role played by nuclear energy and its peaceful applications in addressing the climate crisis at COP28, to be held in Dubai, United Arab Emirates.

For decades, nuclear science and technology have risen to the occasion in helping countries meet their development needs. They can certainly do more, and in more areas. By highlighting the key developments in nuclear technology in 2022, *Nuclear Technology Review 2023* will help Member States make informed decisions on the appropriate route to take for facing current and new challenges.

FIG. FW-1. Rafael Mariano Grossi, IAEA Director General, speaking at the 2022 Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27), held in Sharm El-Sheikh, Egypt. (Photo: IAEA)

Executive Summary

For the second consecutive year, the Agency has revised upwards its annual projections of the potential growth of nuclear power in the coming decades, to reflect a shift in the global debate about energy and the environment amid growing concerns over energy security and climate change. The increasing penetration of variable renewable energy sources can be a cause of instability for electrical grids, which nuclear power plants (NPPs) can compensate through a stable, clean energy supply. The Agency has increased its high case projection to 873 gigawatts (GW) in 2050, up 10% from the previous year's high case scenario. Depending on the level of global electrification, the share of nuclear power could represent up to 14% of the electricity mix in 2050, a substantial increase from the current figure of 9.8%.

At the end of 2022, global operating nuclear power capacity amounted to 393.8 gigawatts (electrical) (GW(e)), provided by 438 operational reactors in 32 countries. In 2022, over 7.4 GW(e) of new capacity was connected to the grid in five countries. According to the reports provided by the relevant countries to the Agency, the nuclear power fleet generated about 2486.8 terrawatt-hours of low-emission, dispatchable electricity.

The energy crisis in 2022 has put on hold some decisions regarding reactor shutdowns, driving operators and regulators to implement actions to ensure safe and reliable long term operation (LTO). The continued and increasing demand for safe, clean, reliable and cost-effective electricity generation is a strong driver for operators to extend the operating life of NPPs by several decades through plant modernization and the enhancement of major equipment and systems to support LTO.

Among the 50 Member States that have expressed interest in introducing nuclear power, 24 are in a pre-decision phase and engaged in planning activities. The remaining 26 countries are pursuing the introduction of nuclear power. By 2035, the number of operating countries may increase by about 30%, with a further 10–12 countries operating NPPs in comparison to the current 32 countries. This growing interest in introducing nuclear power requires adequate nuclear infrastructure development.

Water cooled reactors (WCRs) continue to play a substantial role in the commercial nuclear industry, currently accounting for more than 95% of all operating civilian power reactors in the world. Global nuclear power technology development is focused on accelerating the deployment of advanced reactors, especially small and medium sized or modular reactors (SMRs), as well as on expanding the use of nuclear power to non-electric applications such as district heating, hydrogen production and desalination.

The cogeneration of electricity and heat for non-electric applications of nuclear energy is a reliable and proven technology, with a growing interest worldwide, broad market prospects and development potential. Hydrogen production using either electricity or heat from nuclear reactors is being considered by several countries as well as water desalination.

The technological development attracting the attention of energy planners and policymakers is the expected availability and deployment of several first-of-a-kind SMR designs by 2030. As a result, several newcomer countries have included SMRs in their technology considerations or continue to monitor the developments. There are more than 80 SMR designs from major lines of technology at different stages of development and deployment in 18 Member States. Substantial industrial and regulatory efforts are ongoing to facilitate design development and early deployment, including through the IAEA's SMR Platform and the Nuclear Harmonization and Standardization Initiative.

With the advent of powerful computing capabilities and data analysis tools, the nuclear industry is embracing artificial intelligence (AI), machine learning (ML) and deep learning techniques, to renovate operation systems and short- and long-term maintenance systems as well as advanced manufacturing techniques. Blockchain technology is demonstrating a variety of potential applications along the whole nuclear power supply chain.

In addition to nuclear fusion experimental science, Member States are accelerating nuclear fusion technology development with its emergence in the private sector, the subsequent significant increase in capital invested and recent breakthroughs, as well as the progress of large-scale international and national fusion projects. AI-based modelling of plasma dynamics and real-time control of fusion experiments have seen huge improvements in their efficacy, offering an accelerated path towards fusion energy.

There has been good progress in the ITER project's first plasma operations. In June 2022, the project reached the milestone of 77% completion. However, delays in the original workplan are expected due to the impact of the COVID-19 pandemic and technical challenges such as the need for repair of some key components.

The sustained increase in the uranium spot price has reinvigorated the uranium production industry, and several primary producers are seeking to restart their operations that were placed under care and maintenance owing to a low spot price. With positive signals in the uranium market in the past two years, exploration activity is increasing.

Spent nuclear fuel (SNF) is accumulating in storage at a rate of approximately 7000 tonnes of heavy metal (t HM) per year globally, and the stored inventory is around 320 000 t HM. For countries with long established nuclear programmes pursuing open cycle strategies, the main challenges remain the requirement for additional SNF storage capacity and the increasing storage duration prior to disposal. For countries pursuing closed nuclear fuel cycle strategies, SNF can be reprocessed and recycled for further fuel production.

Digital technologies play an increasingly important role in advancing nuclear decommissioning projects by enabling improved planning and implementation, including the improved visualization of decommissioning scenarios, both by operators and external stakeholders. Augmented reality and virtual reality are being intensively explored to support decommissioning activities and the training of operators.

An emerging trend in environmental remediation is to expand the concept of harm reduction to aggregating value for a contaminated site. Remediation is also a critical phase of mining operations as part of a circular economy because it provides the opportunity to regenerate the site for future productive purposes.

Solid progress in radioactive waste management continued to be made in 2022, particularly in the advancement of deep geological repository (DGR) programmes and the continued safe deployment of predisposal technologies.

There has been an increase in the return of disused high activity sources to suppliers for recycling and disposal. Over 30 high activity sources are planned to be removed from over a dozen Member States in 2023. While many countries have made progress with regard to the management of disused sealed radioactive sources (DSRSs), disposal of DSRSs is still a challenge, especially in countries with smaller nuclear programmes.

Global interest in research reactors continued to grow. In addition to 233 operational research reactors, 11 were under construction. The share of research reactors operating for at least 40 years is approaching 70%. Some organizations operating highly utilized research reactors are considering the extension of their active lifetime to 80–100 years.

Larger-scale AI applications have been revolutionizing the world of high-energy physics. As hadron accelerators are being upgraded to higher luminosities, the number of particles produced per collision is increasing. As a consequence, tracking detectors need to operate at higher counting rates, potentially with higher background counts, as rare probe discovery channels are targeted.

The trend towards using uncrewed aerial vehicles (UAVs) for radiation detection and surveillance is currently influenced by new parameters towards higher payload, safety and flight durability, resistance, and guidance accuracy. New commercially available UAVs for radiation detection and gamma spectrometry have emerged, offering a comprehensive solution for radiological mapping and other applications.

Recent crises and emergencies such as the COVID-19 pandemic, conflicts and climate-related natural disasters have highlighted the vulnerability of the worldwide food supply to stress situations, as well as the need to increase resilience by reforming food control systems and improving technical support. The application of new and emerging nuclear analytical techniques for food analysis in the field can enable effective response to situations affecting the food supply and food security.

At least 1 type of food commodity is currently irradiated in about 70 countries to improve food safety, maintain food quality and extend shelf life. Owing to both economic and practical advantages, the use of machine source irradiation, e.g. using low energy beams (soft electrons or soft X-rays), is expanding. Such alternative technologies help complement the available capacity of gamma facilities and enable the wider use of food irradiation.

In theranostics, a radionuclide for diagnosing cancer is used in combination with another one for therapy. Recent advances in molecular imaging as well as in therapeutical applications, require additional, emerging radioisotopes to be available to clinicians. Thanks to technology developments in radionuclide production, the list of promising radionuclides for radiopharmaceutical applications is growing, which will help improve patient outcomes.

Being the only radioactive isotope within the water molecule, tritium is a valuable tracer of water cycle processes, helping estimate groundwater recharge and assess vulnerability to pollution. Owing to the current low tritium concentration in natural waters, standard measurement methods require significant and time-consuming tritium enrichment to obtain accurate and precise results. A new tritium enrichment system developed by the Agency promises to revolutionize the ability of Member States to determine the concentration of tritium in water samples at ultra-low levels for hydrological monitoring purposes.

About half of all cancer patients need radiotherapy at some point. Artificial intelligence (AI) could offer a solution to the global shortage of health care workers. AI can increase quality and standardization and save time, especially in contouring, a critical step in radiotherapy, during which organs, normal tissues and the tumour are delineated. Hybrid intelligence, which combines the strengths of both natural intelligence and AI, could be used for challenging contours requiring manual adjustments or checking.

The warning signals of a ‘silent pandemic’ of contaminants of emerging concern (CECs) are clear. CECs are chemical substances detected in the environment that do not fall under regulatory surveillance programmes. Passive sampling techniques can detect thousands of chemicals present in the marine environment and facilitate the identification of previously unknown compounds. Breakthroughs in water sampling and advanced analytical screening techniques can help address some of the challenges presented by complex mixtures of CECs present in the marine environment.

Radiotracers are used to track the movement of seawater and to understand marine and coastal ecosystems. They enable the monitoring of radioactive and non-radioactive contaminants, such as microplastics and methyl mercury, and help identify and quantify biotoxins in seafood, assess impacts of ocean acidification on calcifying organisms and evaluate metabolic processes with increasing temperatures. Recent advances in mass spectrometry have opened up possibilities for detecting and analysing long lived radionuclides at extremely low concentrations.

A.

Nuclear Power

A.

Nuclear Power

A.1.

Nuclear Power Projections

Status

For a second successive year, the Agency has revised its annual projections of the potential growth of nuclear power in the coming decades, to reflect a shift in the global debate about energy and the environment amid growing concerns over energy security and climate change.

In its new outlook for global nuclear capacity for electricity generation, the Agency has increased its high case projection to 873 gigawatts (GW) in 2050, up 10% from the previous year's high case scenario. The realization of this projection would require large-scale implementation of long term operation (LTO) across the existing fleet and nearly 600 GW of new build capacity in the coming three decades. This would require on-time and within-budget delivery from the industry, the facilitation of access to financing, and progress towards the harmonization of regulatory requirements and the standardization of industrial approaches. Such actions are of particular importance for new technologies such as small and medium sized or modular reactors (SMRs) and other advanced reactors, which are expected to play a key role in the decarbonization of the energy sector through the supply of low-carbon heat or hydrogen to sectors that cannot be electrified.

873 GW

in 2050

Depending on the level of global electrification, the share of nuclear power could represent up to 14% of the electricity mix, up from the current figure of 9.8%. In the low case, the installed nuclear capacity by 2050 would remain stable at around 400 GW, but the share of nuclear electricity could drop to 6.9% owing to an increased contribution by other sources.

High-level discussions were held at the 27th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27) in Sharm El Sheikh, Egypt in November 2022 on the contribution of nuclear power to affordable, resilient and secure energy supply, as well as on its contribution to decarbonized energy systems, which provide an essential backbone to the deployment of renewables (Figure A.1). Financing the clean energy transition, and financing nuclear projects in particular, remains a challenge, though some positive developments occurred in 2022, such as the inclusion of nuclear power in the European Union's (EU's) sustainable finance taxonomy, as well as in other taxonomies around the world.

Depending on the level of global electrification,
the share of nuclear power could represent

up to **14%** of the electricity mix,
up from **9.8%** today.

In the low case, the installed nuclear capacity
by **2050** would remain stable at around **400 GW,**
but the share of nuclear electricity could drop to **6.9%.**

FIG. A.1. *Agency Director General Rafael Mariano Grossi with Gerd Müller, Director General of the United Nations Industrial Development Organization, and Olga Algayerova, Executive Secretary of the United Nations Economic Commission for Europe, during the COP27 side event "Interplay of Low Carbon Technologies for Resilient Net Zero Energy Systems". (Photo: IAEA)*

Trends

There is considerable and growing interest in advanced and innovative reactor technologies, including in SMRs and their applications. Together with advanced large water cooled reactors, SMRs are expected to make up the bulk of capacity additions over the next three decades for low carbon energy in the fight against climate change and to ensure security of energy supply at an affordable price. The nuclear sector will continue to address a number of challenges, including cost reductions, capacity building, and enhanced harmonization and standardization at regulatory and industrial levels to improve competitiveness and accelerate the deployment of new nuclear power capacity. To support such Member States' efforts, the IAEA Director General has launched in 2022 the Nuclear Harmonization and Standardization Initiative (NHSI) which offers a unique opportunity to all nuclear stakeholders (governments, regulators and industry) to work synergically towards the common goal of the global deployment of safe and secure advanced reactors, with a focus on SMR technology (Fig. A.2).

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

FIG. A.2. *Agency Director General Rafael Mariano Grossi opens the Nuclear Harmonization Standardization Initiative (NHSI) Kick-off meeting held at the Agency headquarters in Vienna, Austria in June 2022. (Photo: IAEA)*

A.2. Operating Power Plants

Status

At the end of 2022, global operating nuclear power capacity amounted to 393.8 (GW(e)), provided by 438 operational reactors in 32 countries. Over 22.8 GW(e) of the total avaialable operational capacity (27 reactors) was in suspended operations status during 2022.

At the end of 2022, global operating nuclear power capacity amounted to
393.8 GW(e)
generated by
438 operational reactors
in **32** countries

Over 7.4 GW(e) of new capacity was connected to the grid in 2022, including 5.6 GW(e) of additional operational capacity in Asia, and 1.6 GW(e) in Europe. In China, two reactors began supplying electricity to the grid in 2022: Fuqing-6 (1075 megawatts (electrical) (MW(e))) — the second of two demonstration Hualong One (HPR1000) reactors at the site — was connected to the grid in January, and Hongyanhe-6 in Liaoning province — a third-generation ACPR-1000 pressurized water reactor (PWR) with a total capacity of 1061 MW(e) — was connected to the grid in May. In the Republic of Korea, a 1340 MW(e) PWR (APR-1400) at the Hanul nuclear power plant (NPP) was connected to the grid in June.

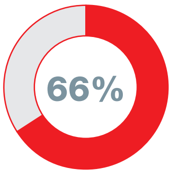
A HPR1000 reactor supplied by China was connected to the grid in March at Karachi NPP in the Sindh province of southern Pakistan. Unit 3 at Barakah NPP in the United Arab Emirates started operations in October, adding 1345 MW(e) of nuclear capacity. The Olkiluoto-3 1600 MW(e) EPR reactor in Finland was connected to the grid in March.

At the end of 2022, a total capacity of 59.3 GW(e) (58 reactors) was under construction in 18 countries. Installed nuclear power capacity under construction has remained largely steady in recent years, except for in Asia, where there has been continuous growth, with 56.1 GW(e) (55 reactors) of operational capacity being connected to the grid since 2012.

At the end of 2022,
a total capacity of
59.3 GW(e)
58 reactors
was under construction
in **18** countries

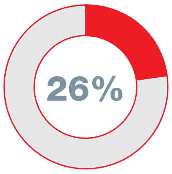
About 66% of global operational reactor capacity (258.7 GW(e), 291 reactors) has been in operation for over 30 years, while over 26% (101.5 GW(e), 128 reactors) has been in operation for over 40 years and 3% (11 GW(e), 13 reactors) for over 50 years. The ageing fleet highlights the need for new or uprated nuclear capacity to offset planned retirements and contribute to sustainability and global energy security and climate change objectives. Governments, utilities and other stakeholders are investing in LTO and ageing management programmes for an increasing number of reactors to ensure sustainable operation and a smooth transition to new capacity.

258.7 GW(e)
291 reactors



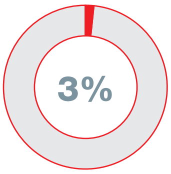
in operation
for over 30 years

101.5 GW(e)
128 reactors



in operation
for over 40 years

11 GW(e)
13 reactors



in operation
for over 50 years

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.

Trends

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

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

A.3.
New or Expanding Nuclear Power Programmes

Status

Among the 50 Member States that have expressed interest in introducing nuclear power, 24 are in a pre-decision phase and engaged in planning activities. The remaining 26 countries are pursuing the introduction of nuclear power within two distinct groups:

- 16 are in a decision phase — countries considering nuclear power, including those that are performing pre-feasibility studies or actively preparing the infrastructure without having made a decision (Algeria, El Salvador, Estonia, Ethiopia, Indonesia, Kazakhstan, Morocco, the Niger, the Philippines, Senegal, Sri Lanka, Sudan, Thailand, Tunisia, Uganda and Zambia).
- 10 are in a post-decision phase — countries that have decided and are building the infrastructure or have signed a contract and will start construction in the near future or have already started construction (Bangladesh, Egypt, Ghana, Jordan, Kenya, Nigeria, Poland, Saudi Arabia, Türkiye and Uzbekistan).

26 Newcomers

16

Decision-making phase

Countries considering nuclear power without having made a final decision

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

10

Post-decision-making phase

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

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

In Bangladesh, construction of the first NPP is ongoing, with planned fuel delivery on site in 2023 and commercial operation for the two units in the coming years. The construction of four units at Akkuyu NPP in Türkiye continued in 2022. Commissioning of the four units is anticipated for 2023–2026. The first concrete of the Egypt's NPP El Dabaa Unit 1 was poured in July and the Unit 2 in November 2022. The Nuclear Power Plant Authority (NPPA) also applied for a construction licence for Units 3 and 4 in 2021. Site preparation for construction continues. Both key organizations (the NPPA and the Egyptian Nuclear and Radiological Regulatory Authority) continue to develop organizational capacity based on the needs of the programme. In Poland, the technology and vendor selection for the construction of PWRs with a total of 6000–9000 MW(e) installed nuclear power capacity by 2042 was completed.

In Saudi Arabia, the bid invitation specification (BIS) for the procurement of the first two NPP units of 1000–1600 MW(e) was released. Jordan has started a feasibility study to identify the preferred technology, the vendor and to make an investment decision for the use of SMRs for electricity production and seawater desalination. The BIS for the SMR project is planned for 2026. Ghana continued to work on developing its national infrastructure for a nuclear power programme, including further development of the capacities of the key organizations. Ghana expanded its choice of reactor technology to SMRs, and a request for interest of potential vendors for the development of around 1000 MW(e) capacity was answered by five vendors. The start of construction of the first NPP is planned for 2023 and commissioning in 2029. Kenya has announced that it will consider the construction of a research reactor and SMRs instead of large NPPs. In Uzbekistan, site characterization and licensing for NPPs with a total of 2400 GW(e) of installed capacity has started. The commissioning of the first NPP is planned for 2026–2030. The Philippines' national position for a nuclear energy programme based on a study conducted by the Government was signed in 2022. This decision paved the way for conducting further studies and assessment of available options between large reactors, including the possible rehabilitation of Bataan NPP, or SMRs. Estonia is considering SMRs for its nuclear power programme, and an interim report was prepared by the nuclear energy implementing organization for the Government, evaluating the conditions for and the viability of a nuclear power programme based on SMRs. For many of these countries, the introduction of nuclear power in the energy mix represents a significant contribution to their climate mitigation objectives. Several of them (Egypt, Jordan and Türkiye) have included nuclear power in their nationally determined contributions submitted to the United Nations Framework Convention on Climate Change under the Paris Agreement.

In 2022, one Agency Integrated Nuclear Infrastructure Review (INIR) mission was hosted by Sri Lanka (Phase 1). The Agency also received requests for an INIR Phase 1 mission from Estonia, an INIR Phase 1 follow-up mission from Kazakhstan and an INIR Phase 3 mission from Türkiye. In December 2021 the Agency received a request for INIR Phase 3 in Bangladesh, that will be implemented in the beginning of 2024. Furthermore, 15 Member States have active Integrated Work Plans, and activities have resumed as COVID-19 related restrictions have been eased.

Trends

By 2035, the number of operating countries may increase by about 30%, with 10–12 new countries operating NPPs in comparison to the current 32 countries. This significant increase requires a further stepping up of the infrastructure preparedness of those countries with Agency support to ensure responsible deployment.

By **2035**
the number of operating countries
may increase by about **30%**
with **10–12** new countries
operating NPPs.

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

At the same time, the progress of the ten Member States embarking on the development of their nuclear power programmes based on evolutionary NPPs shows continued interest in large-scale NPP technology. Member States are reporting their aim of using reference design in operation, and benefit from the experience gained by regulators and operators in the country of origin.

Irrespective of whether a programme is based on large NPPs or SMRs, the national nuclear power infrastructure issues, including nuclear safety, nuclear security, safeguards requirements, should be properly addressed.

A.4.
Nuclear Power Technology Development

Status

Global nuclear power technology development is focused on accelerating the deployment of advanced, including innovative reactors such as SMRs, as well as on expanding the use of nuclear power to non-electric applications such as district heating, hydrogen production and desalination. There is also clear interest from non-traditional stakeholders in using nuclear power to decarbonize the industrial sector, particularly in energy intensive industrial activities. In some parts of the world, stakeholders are looking at applications of nuclear power such as floating NPPs to be operated in cogeneration mode, microreactors for niche applications (in remote regions and small islands, in the replacement of diesel generators, etc.) and nuclear power for space applications. Owing to the increasing penetration of variable renewable energies, which cause stress on electrical grids, advanced reactors are gaining momentum as a clean solution to provide flexibility to electrical rids. Finally, with the advent of powerful computing capabilities and data analysis tools, the nuclear industry is embracing artificial intelligence (AI), in particular machine learning (ML) and deep learning techniques to renovate operation systems as well as short- and long-term maintenance systems.

Trends

In addition to Member States’ efforts in advanced reactor technology development, an increasing number of private companies and start-ups are developing new models of reactors, which are attracting public and private funding. Such companies bring disruptive business models and innovative methodologies, such as the use of digital twins, advanced manufacturing techniques, AI and ML techniques for a wide range of activities that could transform the way nuclear systems are designed, licensed and operated. AI has the potential to enhance the integration of computations and experimental data collected from small-scale experiments or from sensors during operation. This integration, when optimized, allows computational scientists to develop physics models of unprecedented accuracy and helps experimental scientists to minimize the cost and number of validation experiments for first-of-a-kind systems. It also makes it possible for system operators to monitor system states that cannot be directly instrumented. AI methodologies and tools can be applied for physics-based predictive analysis that can be used to perform design, manufacturing and construction optimization, operation effectiveness, improved new reactor design iterations, model-based fault detection and advanced control systems. AI can also bring further benefits to the nuclear industry in terms of reliability, safety and overall efficiency.

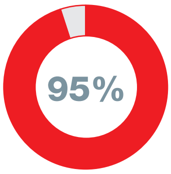
A.4.1.
Advanced Water Cooled Reactors

Status

Water cooled reactors (WCRs) continue to play a substantial role in the commercial nuclear industry, amounting to over 19 000 reactor-years of operation, and currently account for more than 95% of all operating civilian power reactors in the world. As of the end of 2022, 54 out of 57 nuclear reactors under construction are cooled with light or heavy water. Major developments in the WCR sector in 2022 involve new connections to the grid in China, Finland, Pakistan, the Republic of Korea and the United Arab Emirates.

Water cooled reactors

19 000
reactor-years



of all operating
civilian power reactors
in the world

Advanced versions of existing WCRs are also increasingly being considered, studied and implemented in several countries for the gradual deployment of advanced and more efficient partially or fully closed fuel cycles. Several Member States continue with the research and development (R&D) of supercritical water cooled reactors (SCWRs). The conceptual designs of the Canadian SCWR, a heavy water moderated pressure tube reactor concept, and the Chinese CSR1000 were completed. In Europe, the High Performance Light Water Reactor concept was created, and an in-pile fuel qualification test facility was planned, designed and analysed in collaboration with China. In the Russian Federation, conceptual studies on innovative water cooled, water moderated power reactors of supercritical pressure are ongoing, including the possibility of a fast-spectrum core. The recent designs are focused on small modular versions of SCWR designs, emphasizing enhanced safety, security, economics, and sustainability.

Member States are diligently focusing their efforts on developing integrated energy systems that couple renewables — especially solar and wind, which are variable sources of energy — with NPPs, to provide base power load and enhance the stability of the grid, as well as for non-electric applications.

Trends

The power outputs of advanced WCRs under construction vary from 1000 to 1700 MW(e) per unit, and further increases are targeted in the design phase of evolutionary large WCRs. There is a continuing trend towards multi-unit sites with a single or multiple reactor types among Member States. About 30 countries that currently have no operating NPPs are considering building either large or small WCR units.

The continued and increasing demand for safe, clean, reliable and cost-effective electricity generation is a strong driver for operators to extend the operating life of NPPs by several decades through plant modernization and the enhancement of major equipment and systems to support LTO.

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

Status

There are more than 80 SMR designs from major lines of technology at different stages of development and deployment in 18 Member States. Major deployment achievements have been made in the past three years. The Akademik Lomonosov floating NPP in the Russian Federation, with two KLT-40S PWR modules, was connected to the grid in December 2019 and started commercial operation in May 2020, generating 70 MW(e). In China, in an attempt to realize innovative technology for a very high temperature reactor, the High Temperature Reactor–Pebble-Bed Module (HTR–PM) demonstrator was connected to the grid in December 2021 and reached initial full power of 210 MW(e) in December 2022.

80
SMR designs
in **18** Member States

In Argentina, the CAREM-25 reactor, based on an integral PWR with natural circulation, is in an advanced stage of construction and is expected to reach first criticality in 2026. The construction of the ACP100 reactor, intended as a multipurpose reactor, started in July 2021 in China and is planned to start commercial operation by the end of 2026. The construction of an SMR based on the RITM-200N reactor is ongoing in Yakutia, Russian Federation; the project has received environmental approval and is expected to start commercial operation in 2028. The construction of the first floating NPP based on the RITM-200 reactor started in August 2022, and an optimized floating power unit based on the RITM-400 reactor is being developed in the Russian Federation. In the United States of America, in July 2022, the Nuclear Regulatory Commission approved a design certification for an initial NuScale Power plant design. NuScale submitted a standard design approval application in December 2022 for an uprated power module in a six-module configuration to be demonstrated at the Idaho National Laboratory in 2029. France is developing NUWARD, an integrated PWR design to generate 340 MW(e) from two independent reactor units of 170 MW(e) each to enable flexible operation. The first concrete for the first-of-a-kind NUWARD reactor will be poured in France by 2030. NUWARD is a case study SMR for a European early joint review led by the French Nuclear Safety Authority, with the participation of the Czech State Office for Nuclear Safety and the Finnish Radiation and Nuclear Safety Authority. In the United Kingdom, the Office for Nuclear Regulation is conducting a generic design assessment for the Rolls-Royce SMR, a three-loop PWR designed to generate 470 MW(e), with the start of construction planned for 2026. There are also SMR designs based on boiling water reactor technology with natural circulation. The US Nuclear Regulatory Commission and the Canadian Nuclear Safety Commission are reviewing a licence to construct application for BWRX-300, a 300 MW(e) design that originated in the United States of America, for planned deployment at the Darlington NPP in Ontario, Canada and at the Clinch River site in Tennessee, United States of America. The Canadian Small Modular Reactor Action Plan also outlines the planned deployment of the Micro Modular Reactor (MMR), a microreactor with modular high temperature gas cooled reactor (MHTGR) technology, to generate 15 MW(th) for the cogeneration of electricity and industrial process heat at Chalk River Laboratories. In the Republic of Korea, the 110 MW(e) system-integrated modular advanced reactor (SMART) design is undergoing a licensing process to obtain joint SDA in cooperation with Saudi Arabia. A Korean consortium has started developing an innovative SMR, a 170 MW(e) PWR, to improve safety and economy.

Molten salt reactors (MSR) also belong to the technology line adopted for SMRs. Various MSR designs, in different stages of development, are currently being pursued in Canada, China, Denmark, France, Indonesia, Japan, the Netherlands, the United Kingdom, and the United States of America.

Trends

The interest of Member States in SMRs and their applications has been increasing. Substantial industrial and regulatory efforts are ongoing to facilitate design development and early deployment. Major trends remain towards the field of technology of higher maturity or readiness level, particularly relating to integral WCRs and MHTGRs. Until around 2030, SMR designs using these technologies will be at the forefront of licensing processes, followed by designs for innovative reactors using non-water coolants. In 2022, technology development activities for a subset of SMRs known as microreactors continued in Canada, the Czech Republic, Japan, the Russian Federation, the United Kingdom and the United States of America. Designed to generate a lower range of power up to 10 MW(e), microreactors are envisioned as the optimum solution for providing cogeneration of heat and electricity in remote regions or small islands, and/or to replace diesel generators.

More countries are currently engaged in the design development of marine-based reactors. The Republic of Korea continues the development of BANDI-60, a PWR-based floating power unit to generate 60 MW(e). A reactor design start-up company in Denmark is developing the Compact Molten Salt Reactor to produce approximately 100 MW(e). Marine-based SMRs are designed for niche markets including distributed power and heat supplies to remote communities, desalination, and hybrid energy systems through collaboration with marine and shipbuilding industries.

In this very fast-developing scenario, the IAEA SMR Platform, established in 2021 by the IAEA Director General, is providing a ‘one-stop-shop’ for Member States and other stakeholders interested in SMR development, deployment, and oversight, ensuring Agency’s coordinated and consistent support, including through the newly launched SMR Portal.

A.4.3.
Fast Reactors

Status

In 2022, five sodium cooled fast reactors (SFRs) were in operation in three Members States: one in China, one in India and three in the Russian Federation. India is also commissioning 500 MW(e) Prototype Fast Breeder Reactor, while China is building two SFR units of the same type, CFR-600. While all five operating reactors and all three reactors under construction are cooled by liquid sodium, heavy liquid metal coolant technology is attracting increasing attention, especially in the area of SMRs. The Russian Federation is continuing construction of a 300 MW(e) demonstration lead cooled fast reactor (LFR), BREST-OD-300 (Figure A.3) and the Multipurpose Fast Neutron Research Reactor. Several other promising coolant technologies, such as helium and molten salts, are also under development in several countries. Of six innovative reactor concepts developed by the Generation IV International Forum, three (sodium, heavy liquid metal and helium cooled) are fast neutron systems, while two (molten salt and supercritical water cooled) can operate in either fast or moderate neutron spectrums.

FIG. A.3. BREST-OD-300 site in September 2022. (Photo: ROSATOM)

Trends

SFRs are still the main option for medium-term deployment; the Russian Federation is developing the large 1200 MW(e) BN-1200 reactor, China is planning the 1 GW(e) CFR-1000 reactor, and TerraPower in the United States of America is developing the Natrium reactor combined with molten salt storage that can reach a peak of 500 MW(e). Natrium can replace a typical coal power plant, and it can also work together with other renewables. Several countries are developing LFRs: the United Kingdom–United States of America 450 MW(e) Westinghouse LFR, the Italy–Romania 120 MW(e) Advanced Lead Fast Reactor European Demonstrator (ALFRED), SEALER-55 in Sweden and several LFR designs of SMR type in China. Founded at the end of 2021, the Italy–United Kingdom start-up Newcleo is developing mini (30 MW(e)) and small (200 MW(e)) LFRs. While France has postponed the development of the Advanced Sodium Technological Reactor for Industrial Demonstration, R&D on SFR and the associated fuel cycle is ongoing, and the country is developing a molten salt fast reactor (MSFR) that can work in the uranium–plutonium cycle. The EU is conducting an MSFR project SAMOSAFER to develop and demonstrate new safety barriers for more controlled behaviour in severe accidents.

A.4.4. Non-electric Applications of Nuclear Power

Status

The cogeneration of electricity and heat for non-electric applications of nuclear energy is a reliable and proven technology, with a growing interest worldwide, broad market prospects and development potential, as only a small fraction of nuclear heat is currently utilized directly. A total of about 70 nuclear reactors are being utilized at present for non-electric applications, broadly categorized as desalination, district heating, process heating and hydrogen production. The total nuclear heat utilization in those applications is over 2 TW·h of electrical equivalent each year. Most of these nuclear reactors are utilized to provide

About **70** Nuclear Reactors
are being utilized at present for
non-electric applications

Over **2 TW-h**
of electrical equivalent each year

district heating, and about half of those also provide process heat. About ten are currently utilized to provide energy for nuclear desalination, and a few are in the process of starting pilot-scale demonstrations of hydrogen production.

Joining a group of existing users that includes Bulgaria, the Czech Republic, Hungary, Romania, the Russian Federation, Slovakia, Switzerland and Ukraine, China recently started a major nuclear district heating development programme. Following the start-up of the district heating network connected to Haiyang NPP in Shandong province in 2020, the Hongyanhe project, formally initiated in 2022, will avoid emissions associated with 12 100 tonnes of coal, and emissions of sulphur, carbon dioxide, dust, nitrogen oxide and ash will be reduced. A district heating demonstration project was launched also at the Qinshan NPP in 2021 in Zhejiang province, aiming to have a nuclear heating area of 4 million square metres by 2025, covering the main urban area of Haiyan County and the entire area of Shupu Town.

A number of countries have plans for the deployment of nuclear desalination, joining experienced users of this technology. Several desalination units have been powered by NPPs in Japan and the Russian Federation, while India, which already has long experience in operating desalination units coupled with nuclear reactors, plans an expansion of its nuclear desalination capacity in the coming years.

Hydrogen production using either electricity or heat from nuclear reactors is being considered by several countries including Canada, China, France, Japan, the Republic of Korea, the Russian Federation, Sweden, the United Kingdom and the United States of America. R&D is ongoing for the coupling of high temperature hydrogen production processes with advanced reactors (such as HTR–PM, which recently started operation in China), as well as with the current fleet. For example, in the United States of America, there are five different projects on coupling electrolysers with existing NPPs; four of those involve electrical coupling with low temperature electrolysers, while one, at the Prairie Island NPP, will also utilize nuclear heat to increase the efficiency of hydrogen production (Figure A.4). The Russian Federation intends to demonstrate clean hydrogen

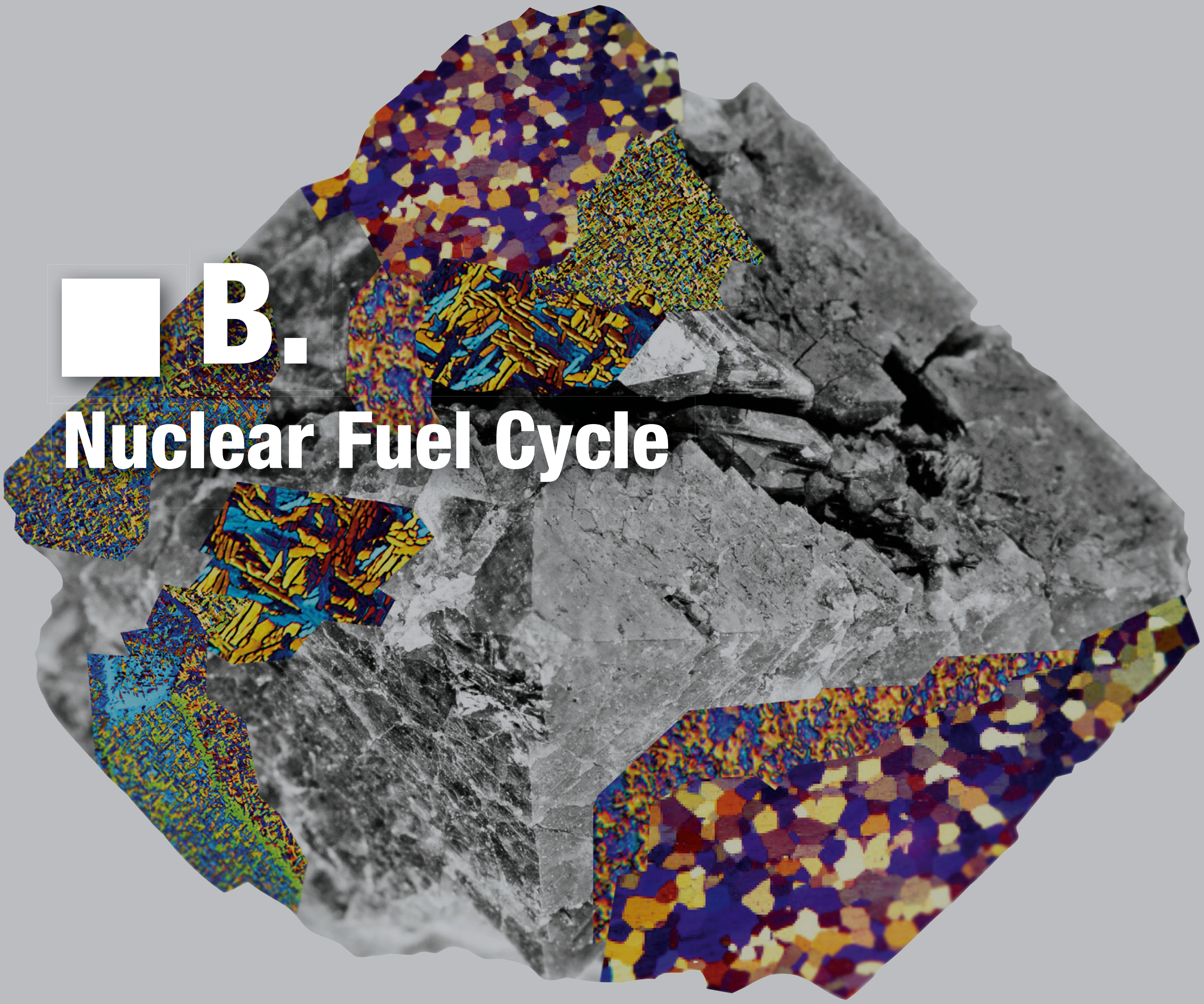
FIG. A.4. The Prairie Island NPP in Minnesota, United States of America, where Xcel Energy and partners are deploying a pilot project on hydrogen generation using a high temperature steam electrolyser. (Photo: Shutterstock) production at the Kola NPP, while France has announced that, by 2030, it aims to start the construction of a small modular reactor and use the existing nuclear fleet to produce clean hydrogen.

Trends

The potential of nuclear energy to supply heat as well as electricity is of growing interest worldwide. This comes in response to increasing efforts to fight climate change, and as many regions of the world are experiencing increasing costs of fossil fuels. As the majority of emissions currently originate from outside the electricity sector, and as almost all the energy for non-electric applications is currently supplied by fossil fuels, nuclear energy is of particular interest as one of the few sources of both electricity and heat that is carbon free, that can be deployed at scale without geographical limitations and that is available around the clock. In addition, SMRs and microreactors offer interesting possibilities because of their smaller size, as several of the heat demand centres are not large enough to effectively utilize the amount of heat generated by the GW-scale plants. Finally, certain advanced reactors, such as the HTR–PM, offer unique possibilities associated with the supply of high temperature heat, which in turn can be effectively utilized in several industrial applications.

B.

Nuclear Fuel Cycle

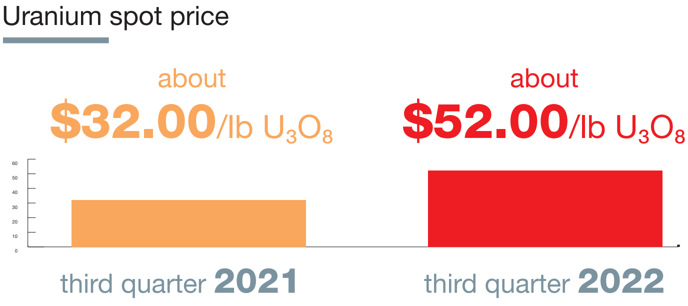


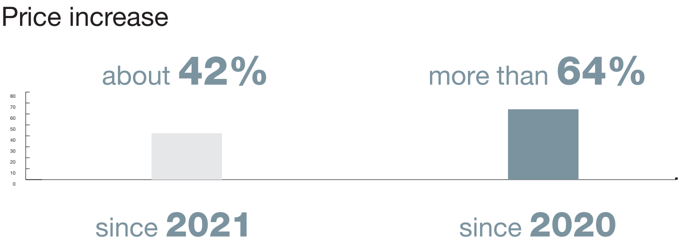
B.
Nuclear Fuel Cycle

B.1.
Front End

Status

In the third quarter of 2022, the uranium spot price was about US $52.00/lb U_3O_8. This is a significant increase from the third quarter of 2021, when it was about $32.00/lb U_3O_8. In addition, the uranium spot price has increased by about 42% since 2021 and more than 64% in the past two years (Figure B.1). This sustained increase in the uranium spot price has reinvigorated the uranium production industry, and several primary producers are seeking to restart their operations that were placed under care and maintenance owing to the low spot price. This includes the McArthur River mine in Canada and the Langer Heinrich mine in Namibia.





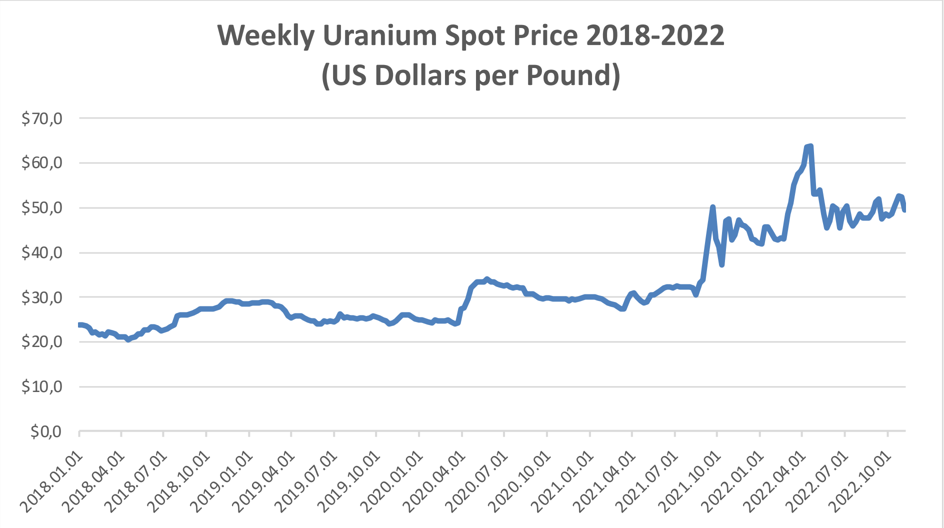


FIG. B.1. Uranium spot price evolution since 2018. (Source: UxC)

Kazakhstan, the country with the highest annual uranium production rates, has announced that it will increase output from its in situ recovery (ISR) operations from about 70% to 90% of nameplate capacity. The Honeymoon mine in Australia has also announced a restart of its ISR mine and processing facility. Uranium exploration reached a low in 2020, with about US $39.2 million spent. With positive signals in the uranium market in the past two years, exploration activity is increasing, and about US $71 million was spent on uranium exploration in 2021.

Nuclear fuel production is a mature technology that has continuously progressed over the years through automation and digitization, reduced operational waste generation and enhanced radiation protection for workers. It has provided for improvements in economics (extension of fuel cycles from 12 months to 18 and 24 months, higher burnups), reliability (reduced fuel failures, new fuel designs to minimize the fuel assembly bow, improved seismic performance, doped fuel, liner and duplex cladding, increased corrosion resistance) and sustainability (the recycling and multi-recycling of fuel for light water reactors (LWRs) and fast reactors). At present, existing nuclear fuel fabrication capacities are sufficient worldwide to cover the anticipated nuclear power demand.

Several Member States — some of them contributing to the Agency CRP “Testing and Simulation for Advanced Technology and Accident Tolerant Fuels (ATF-TS)” — have ongoing RD&D programmes to deploy accident tolerant and advanced technology fuels (ATFs) and innovative fuels, using advanced manufacturing technologies such as additive manufacturing (e.g. 3D printers to form nuclear grade silicon carbide used in ceramic microencapsulated fuels).

Several Member States already recycle fuels in existing reactors and plan to do so for future ones, while others have ongoing RD&D programmes to recycle fuel or to deploy innovative fuels for SMRs. R&D is under way on uranium dioxide and uranium–plutonium mixed oxide (MOX) fuels and ATFs for light/heavy water cooled SMRs; cermet fuel for floating and land-based light water cooled SMRs; TRISO fuels for high temperature gas/molten salt/heat pipe cooled SMRs; metal or ceramic fuels for liquid metal/gas/heat pipe cooled fast SMRs; and molten salt fuels for molten salt cooled SMRs.

Trends

Global forecasts indicate that uranium demand over the next five years will increase from about 160 million pounds U_3O_8 per annum to about 190 million pounds. The global annual production rate of uranium in 2022 is forecast to be about 133 million pounds, with the remainder of the supply made up from ever-decreasing secondary supplies. In anticipation of further increases in the spot price for uranium, it is predicted that NPPs’ procurement departments will be looking to forward purchase uranium ore concentrate and to develop once again long-term contracts with uranium suppliers. This has the potential to further increase the spot price for uranium, which is expected to increase from about US $52.00/lb U_3O_8 to about US $65.00/lb U_3O_8 by 2027.

It is anticipated that new uranium mines will open in the next five to ten years, including in Australia, Brazil, Canada, Mauritania and Namibia. However, forecast production from these new operations will not be sufficient to make up the supply gap that is currently filled with secondary sources. As such, it is anticipated that

Uranium demand global forecasts, per annum

from about **160** million pounds U_3O_8 → to about **190** million pounds U_3O_8

The global annual production rate of uranium in **2022** is forecast to be about **133** million pounds U_3O_8

exploration activity for uranium will increase in the coming years, including in conventional and unconventional deposit types. Considering the long timeline to develop and commission a new uranium mine after a deposit is identified and confirmed (10–15 years), exploration and identification of new uranium reserves is required.

To ensure uranium resources are brought to market when they are needed, future uranium supplies would benefit from timely research and innovation efforts to further improve uranium exploration and to develop new, more cost-effective extraction techniques. As regards the sustainability of the uranium industry, and the recovery from lower grade and more challenging uranium deposits, innovation is required to advance marginal uranium deposits into production. An example of such innovation in the uranium mining industry in 2022 could be found in the positive results achieved in the feasibility studies for developing an ISR mine in a high-grade unconformity type deposit. In addition, the beneficiation or upgrading of low grade uranium shows promise and is making previously uneconomical deposits more attractive. Bioleaching methods are another significant innovation being developed for application in ISR of uranium from sandstone type deposits. Finally, heap leaching techniques, used in other mining applications, are showing promise for some uranium operations.

Following the Fukushima Daiichi nuclear accident in 2011, many Member States' efforts have focused on improving the safety of the fuels used in existing large-scale LWR fleets and of those to be used in future generations of reactors, including SMRs. Many Member States are pursuing intensive programmes to deploy ATFs, involving lead test rod and lead test assembly fabrication, irradiation and post-irradiation examinations, fuel performance assessment, system thermal hydraulics, and severe accident code development and validation.

Some Member States have plans to develop fuel licensing infrastructure to support the extension of burnup and enrichment beyond legacy limits in the mid-2020s, and to safely and economically enable 24-month cycle operation for existing LWRs with increased average burnups and without physical changes to manufacturing plants and transport containers (i.e. only through changes in licensing procedure). A trend towards commercialization and economies of scale for advanced fuel technologies through sustainable volumes is required to meet the domestic and global demand.

Other drivers for nuclear fuel development are innovative reactor designs, such as Generation IV reactors and SMRs (ranging from scaled down versions of LWR fuel designs to entirely new Generation IV fuel designs). The successful deployment of all types of SMR fuels will require the maturity of fuel production technologies from the R&D stage to the industrialization stage. Furthermore, HALEU will be required to manufacture many of the innovative nuclear fuel concepts, such as some ATFs and SMR fuels. Currently, only the Russian Federation has a supply chain for HALEU fuel production, although the United States of America has plans to establish a HALEU infrastructure for advanced reactors.

B.2.
Back End

Status

Spent nuclear fuel (SNF) is accumulating in storage at a rate of approximately 7000 tonnes of heavy metal (t HM) per year globally, and the stored inventory is around 320 000 t HM. For countries with long established nuclear programmes pursuing open cycle strategies, the main challenges remain the requirement for additional SNF storage capacity and the increasing storage duration prior to disposal (Figure B.2).

In some countries, SNF is often moved from wet to dry storage facilities after an initial cooling time. Work to develop centralized interim storage facilities continues. Spent nuclear fuel transportation is a routine operation in some countries, and preparations are under way in others to support future transport campaigns. Member States are continuing with the removal and relocation of their SNFs in the framework of the decommissioning projects of their NPPs.

The United Kingdom ceased reprocessing operations in July 2022 with the closure of the Magnox Reprocessing Plant, which led to a significant reduction of global reprocessing capacity. Development of new recycling technologies for the current fleet and advanced reactor fuels on a commercialized scale continued in France, India and the Russian Federation. In December 2022, the BN-800 reactor in the Russian Federation reached almost 100% loading with MOX fuel as a step of implementing the ‘balanced nuclear fuel cycle’ concept, which envisages reprocessing of SNF, recycling of regenerated nuclear material as nuclear fuel and transmutation of minor actinides in fast neutron reactors. The decision to construct the Pilot Demonstration Energy Complex for the reprocessing of LFR fuel in Seversk, Russian Federation was made, with operations expected to begin in 2024. Various programmes from the US DOE are linking national laboratories with universities and commercial organizations to develop scalable solutions based on technologies such as aqueous reprocessing and pyroprocessing. The Canadian designer of the IMSR, Terrestrial Energy, is partnering with the Australian Nuclear Science and Technology Organisation (ANSTO) to determine whether ANSTO’s Synroc treatment process is suitable for the conditioning of spent fuel salts from the IMSR.

FIG. B.2. Participants of the Agency CRP “Spent Fuel Performance Assessment and Research — Phase IV” visited the new storage facility under construction as part of a technical tour of the Atucha NPP in Argentina, in 2019. (Photo: IAEA)

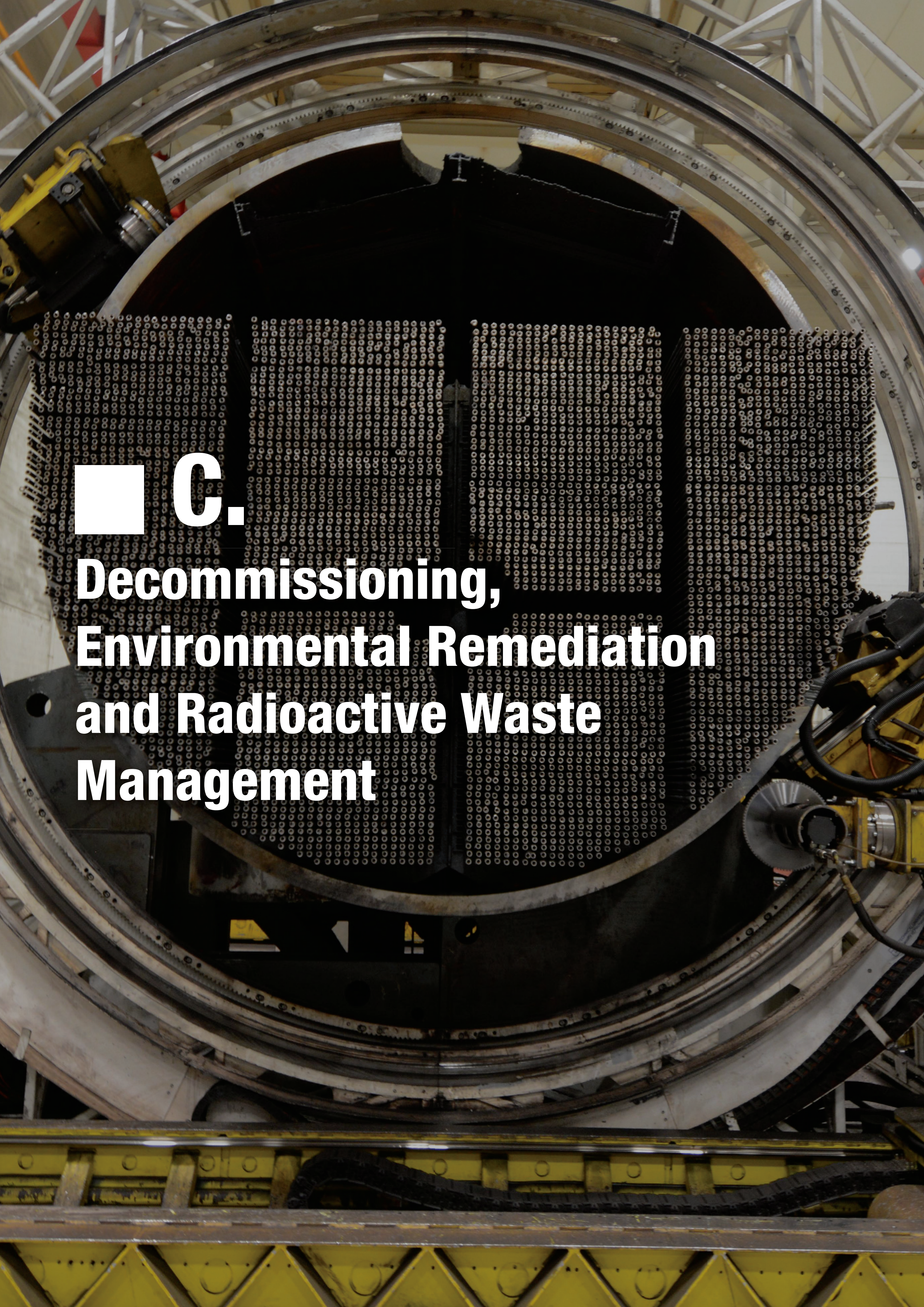
Trends

Understanding the behaviour of SNFs in various storage systems and the ageing and degradation mechanisms of storage structures, systems and components remains vital in ensuring that SNFs can continue to be stored safely and subsequently transported to disposal or reprocessing facilities. As spent fuel disposal programmes are progressing in some Member States, there has been an increase in the number of preparation activities, such as the development of characterization programmes.

The Agency coordinates research activities on this matter to collect Member States' operational experience and research findings, and to foster information sharing. Continuation of such efforts is particularly important when considering that greater reactor efficiencies have been achieved through the production of spent fuel with higher initial enrichments and higher burnups, leading to increases in thermal outputs and potentially higher risks of cladding embrittlement that may impact subsequent spent fuel management steps.

As new fuel designs for both the existing fleet of reactors and advanced reactor designs, including SMRs, are envisaged, which may lead to potentially different behaviours in spent fuel management, innovative spent fuel management solutions will need to be sought to allow for their timely deployment.

Despite an overall reduction in global spent fuel reprocessing capacity, there is an increasing interest in the development of advanced recycling technologies both for current fuels and to support the deployment and sustainability of advanced reactors. 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.



C.

Decommissioning, Environmental Remediation and Radioactive Waste Management

C.

Decommissioning, Environmental Remediation and Radioactive Waste Management

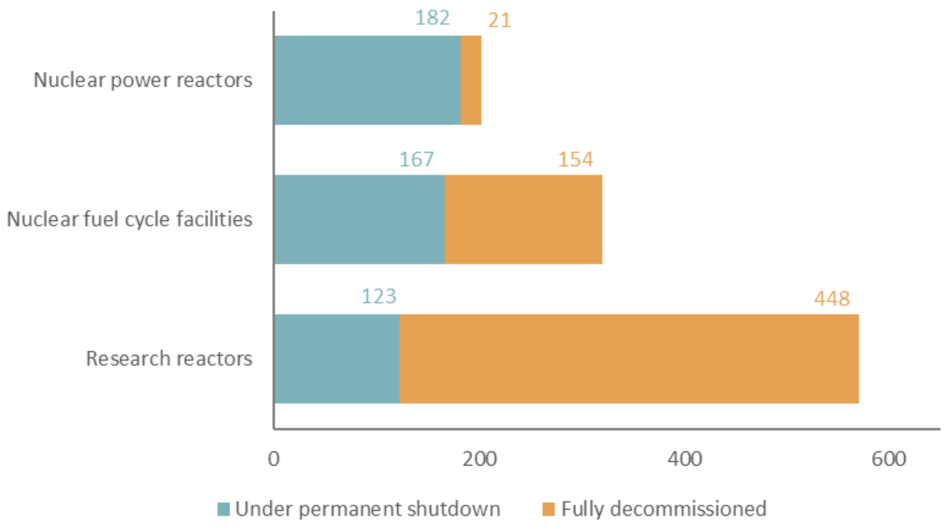
C.1.

Decommissioning

Status

Five power reactors were permanently shut down in 2022: Doel-3 in Belgium, advanced gas cooled reactors (AGRs) Hinkley Point B-1 and B-2 and Hunterston B-2 in the United Kingdom and the Palisades PWR in the United States of America. Globally, 203 nuclear reactors have been permanently retired from service, of which 21 have been fully decommissioned. The main ongoing power reactor decommissioning programmes are in Germany, with 27 reactors under permanent shutdown or currently under decommissioning; Japan, with 24 reactors at the same stages; and the United States of America, with 28 reactors under permanent shutdown or currently under decommissioning, of which 18 are in safe enclosure and 8 are currently being dismantled. The United Kingdom has permanently shut down 36 of its first- and second-generation gas cooled reactors, most of which are in the post-operational phase preparing to enter safe enclosure.

Status of nuclear power reactors, fuel cycle facilities and research reactors in 2022



Decommissioning activities are proceeding at the major fuel cycle facility sites around the world, including at several sites in France, the Russian Federation, the United Kingdom and the United States of America. In general, a major current focus is serious hazard risk reduction, including the removal of legacy waste, typically stored in ponds or in concrete trenches as a precursor to proceeding with facility dismantling. At the Magnox Reprocessing Plant in the United Kingdom, preparations for post-operational cleanout activities are under way. The site is also moving into full operational retrievals mode from its legacy ponds and silos. Removal and conditioning of legacy waste is continuing at the La Hague site in France, including the removal of graphite and magnesium waste stored in concrete silos and the decontamination of cells in which activity levels constrain or preclude human access. The dismantling of all plutonium gloveboxes on this site has also been completed, with the current focus being the dismantling of all the main process equipment — dissolvers, mixer settlers and evaporators.

Significant technical progress was made at various NPPs in 2022, for example, the cutting and packaging of 2 reactor pressure vessels, 12 steam generators and other primary circuit components were completed at Bohunice V-1 NPP in Slovakia (Figure C.1); the cutting of the large rotating plug was finished at Superphénix NPP in France; the dismantling of the reactor core was completed at Vermont Yankee NPP in the United States of America; and the demolition of the last remaining large building, the turbine building, was completed at José Cabrera NPP in Spain.

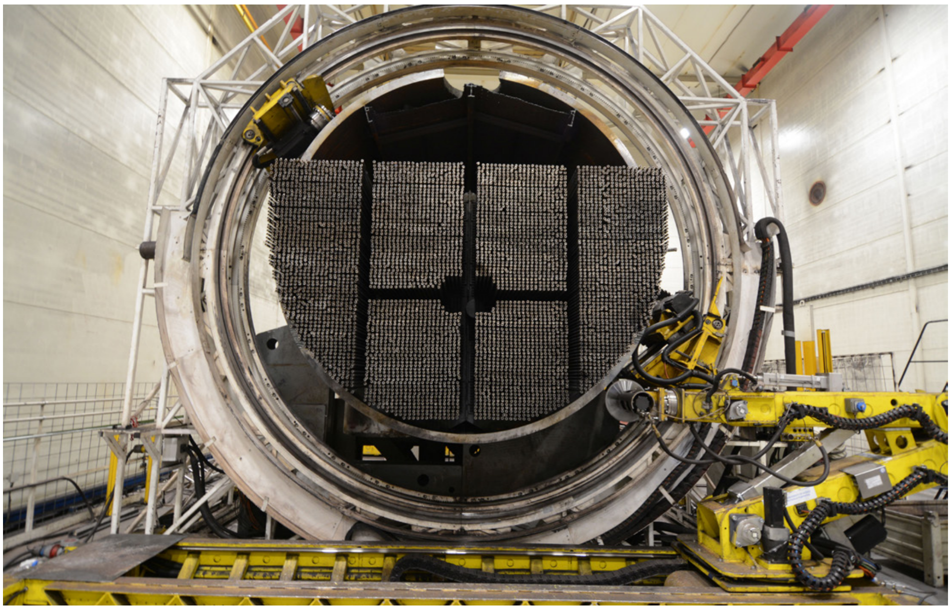


FIG. C.1. Cutting of Bohunice V-1 NPP steam generator. (Photo: Nuclear and Decommissioning Company, Slovakia)

An important milestone was reached within the Japan Atomic Energy Agency back-end programme, with the successful completion of the major parts of the first stage of decommissioning of the MONJU fast breeder reactor; 530 fuel assemblies from the reactor core, as well as the ex-vessel fuel storage tank, were moved to the spent fuel pond in October 2022. The removal of bulk sodium from the primary coolant circuit was completed in April 2022.

On 22 July 2022, the Nuclear Regulation Authority of Japan approved the amendment of the implementation plan pertaining to the installation of the Advanced Liquid Processing System (ALPS) treated water discharge facility which was submitted in December 2021 by Tokyo Electric Power Company. The discharge is scheduled to begin in 2023, and the installation of facilities for the discharge is currently under way. Regarding the retrieval of fuel debris from the reactor vessels, it has been decided that a trial retrieval from Unit 2 will be conducted first. The manufacturing of equipment such as robotic arms and manipulators for this purpose has been completed (Figure C.2), and efforts to improve their operability as well as a detailed investigation of the containment vessel penetration area where the equipment will be installed are currently under way.

FIG. C.2. Testing hall for robotic arms and manipulators for Fukushima Daiichi NPP. (Photo: Ministry of Economy, Trade and Industry, Japan)

Trends

Current projections by the Agency on the evolution of installed nuclear capacity between now and 2050 are presented as ‘high’ and ‘low’ scenarios. In the case of the high scenario, approximately 25% of the current installed capacity would be retired and the lifetimes of many others extended, in addition to an extensive new build programme. As regards the low scenario, up to 75% of the current installed capacity would be retired, and new builds would replace this lost capacity. There is therefore currently a wide range of uncertainty about the pace of shutdowns between now and 2050.

Evolution of the installed nuclear capacity between now and 2050

High scenario	Low scenario
▲	▼
up to **25%** retiredr	up to **75%** etired

As in recent years, nuclear facility shutdowns are occurring at a pace that matches approximately the rate at which new facilities are being commissioned. In the case of NPPs, shutdowns are dominated by the retirement of the United Kingdom’s second generation AGRs for economic reasons, where the costs of extending the lifetime of the facilities does not justify the anticipated income stream from continued operation. In the case of Germany, the final shutdowns of the last three facilities in operation have been delayed from the end of 2022 to April 2023 because of the current energy crisis.

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

Digital technologies and virtual and augmented reality play an increasingly important role in advancing nuclear decommissioning projects by enabling improved planning and implementation. Potential benefits span several areas of activity in the decommissioning stage of the facility life cycle: providing improved means of gathering, analysing and displaying information needed to plan dismantling strategies; using robots to ensure the safety of personnel; facilitating operator training through enabling the simulation of planned activities in a virtual environment with realistic effects; supporting the accurate definition of future waste arisings and thereby improving cost estimation; and enabling the improved visualization of decommissioning scenarios, both by operators and external stakeholders. Digital technologies will bring many more potential benefits to the nuclear industry as a whole, when the knowledge gained at the decommissioning stage will be transferred to NPP designers and operators as well as technical support organizations.

C.2.

Environmental Remediation and Management of Naturally Occurring Radioactive Material

Environmental Remediation

Environmental remediation can be a slow process, and, therefore, progress is steady in some cases. However, in others, barriers for implementation continue to be a challenge. Since 1989 in the United States of America, the Department of Energy’s Office of Environmental Management has completed legacy clean-up at 92 sites across the country, with the most recent completion at Brookhaven National Laboratory. Fifteen sites remain and involve some of the toughest and most expensive challenges. Efforts to overcome the legacy of uranium mining in Europe and Central Asia are making progress. An emerging technology combining a drone with a highly sensitive gamma ray detector has been developed and will be deployed in the near future to assist in the characterization of sites contaminated by former uranium operations in Central Asia. In order to address the need for specialized workforces in both decommissioning and remediation, a consortium led by the University of Porto in Portugal is developing a Master of Science programme in decommissioning and environmental remediation under the auspices of the European Commission’s Erasmus+ programme.

Management of Naturally Occurring Radioactive Material

Many countries are facing challenges in managing their naturally occurring radioactive material (NORM) residues (Figure C.3). Support is being sought to introduce the infrastructure necessary to cope with their needs. Bottlenecks are created due to the lack of policies surrounding the use of NORM residues and the disposal options for NORM when it is declared waste. The absence of accredited laboratories in many Member States constitutes another obstacle adding to the challenges related to transportation of these materials for disposal in another country.

FIG. C.3. Residues from the copper mining industry with the presence of NORM. (Photo: IAEA)

Trends

Environmental Remediation

An emerging trend in remediation is to expand the concept of harm reduction to aggregating value for a contaminated site. Reprocessing existing, older wastes can eliminate costly remediation by geochemically and geotechnically stabilizing residues. This will reduce liabilities and associated final closure costs and may create marketable 'green' products. Remediation is a critical phase of mining operations as part of a circular economy because it provides the opportunity to regenerate the site for future productive purposes. One example is a programme initiated in the United States of America, which is allocating significant resources to develop clean energy on former mining lands, transforming these sites into clean energy hubs.

For ongoing and future projects, it is critical to begin planning for closure at the inception of the project. However, engaging fully with these opportunities at the site level requires an expanded circular economy model that acknowledges established approaches to sustainability that should embrace environmental, economic and social dimensions within a framework of a participatory decision-making process. In this regard, there is a trend towards adopting AI and ML to support decision-making in complex situations such as in the scope of environmental remediation.

Management of Naturally Occurring Radioactive Material

Circularity is also present in NORM management-related activities. Different industries are studying the processes that can add value to NORM residues. Evidence of a growing trend in this direction may be found in the use of phosphogypsum in agriculture as soil amendment and as a building material, and in the use of ilmenite mud in commercial cement manufacturing and ceramics manufacturing, among others. Taking full advantage of residues generated in NORM-related industrial processes will require investments in technological innovation, appropriate policies at the national level, knowledge of inventory of such materials and innovative financing mechanisms, so that alignment with the 2030 Agenda for Sustainable Development can be realized.

C.3.

Radioactive Waste Management

Status

Solid progress in radioactive waste management continued to be made in 2022, particularly in the advancement of deep geological repository (DGR) programmes and the continued safe deployment of predisposal technologies.

While technologies for the conditioning and treatment of the vast majority of radioactive waste streams are available and are being implemented, there is a challenge in identifying the techniques most suitable from both a technical and funding perspective. Technology selection requires knowledge of the waste and its characteristics, the applicable waste acceptance criteria (WAC), and understanding of the governing regulatory requirements. Characterization capabilities have been developed by the Pakistan Atomic Energy Commission for both NPP waste and decommissioning waste. Along with the characterisation capabilities, the development of WAC for the low and intermediate level waste (LILW) disposal facilities is progressing. Centralized solutions for predisposal waste management are being developed in several countries with small inventories. Croatia has decided to establish a radioactive waste management centre at Čerkezovac, and Estonia has decommissioned the RADON-type facility and transferred all the waste to facilities at the Paldiski site.

After a comprehensive programme to ensure safe operational conditions, radioactive waste processing and disposal activities have resumed at Ukraine's Chornobyl site following the shutdown of these facilities in February 2022.

Through the Agency's on Global Radium-226 Management Initiative, several Member States have already found an outlet for disused radium sources. In Iceland, radium-226 sources have been conditioned to facilitate transport for recycling into radiopharmaceuticals, which provide targeted alpha therapy of cancerous cells (Figure C.4).

In 2020, Canada launched an inclusive engagement process to modernize its radioactive waste policy, and, in February of 2022, released its draft Policy for Radioactive Waste and Decommissioning for public comment. A national integrated strategy for Canada's radioactive waste management strategy was

FIG. C.4. Spent radium needles conditioned in Iceland for recycling purposes. (Photo: IAEA)

released for public comment in August 2022, with a focus on informed waste management, where all waste streams in the national inventory have a planned disposal solution. The Canadian Nuclear Laboratories announced in May 2022 that the Port Granby Project was in long-term maintenance and monitoring following the emplacement of 1.3 million tonnes of low level waste in an above-ground engineered containment mound that was closed in late 2021.

Several developments have taken place in DGR programmes for high level waste. The Finnish waste management organization Posiva completed the excavation of the first five disposal tunnels in preparation for the start of the final disposal of spent fuel by 2025. In January 2022, the Swedish Government granted the Swedish Nuclear Fuel and Waste Management Company permission to begin construction of the spent fuel repository in Forsmark, as well as the encapsulation plant in Oskarshamn. A subsequent public opinion poll at the Östhammar municipality site revealed that over 80% of respondents were in favour of the DGR construction, the highest approval ever. Under the Cigeo project in France, plans were in place to apply for a construction licence before the end of 2022. In the Russian Federation, full-scale and laboratory studies of the rock mass for the construction of a DGR laboratory in Krasnoyarsk region are expected to be completed in 2023.

In terms of siting for a DGR, Switzerland's National Cooperative for the Disposal of Radioactive Waste provided a site recommendation for Nördlich Lägern in September 2022 and is to submit the licensing application in 2024. Canada's Nuclear Waste Management Organization continues engaging with volunteer communities and intends to recommend a site to host a DGR in 2024.

Trends

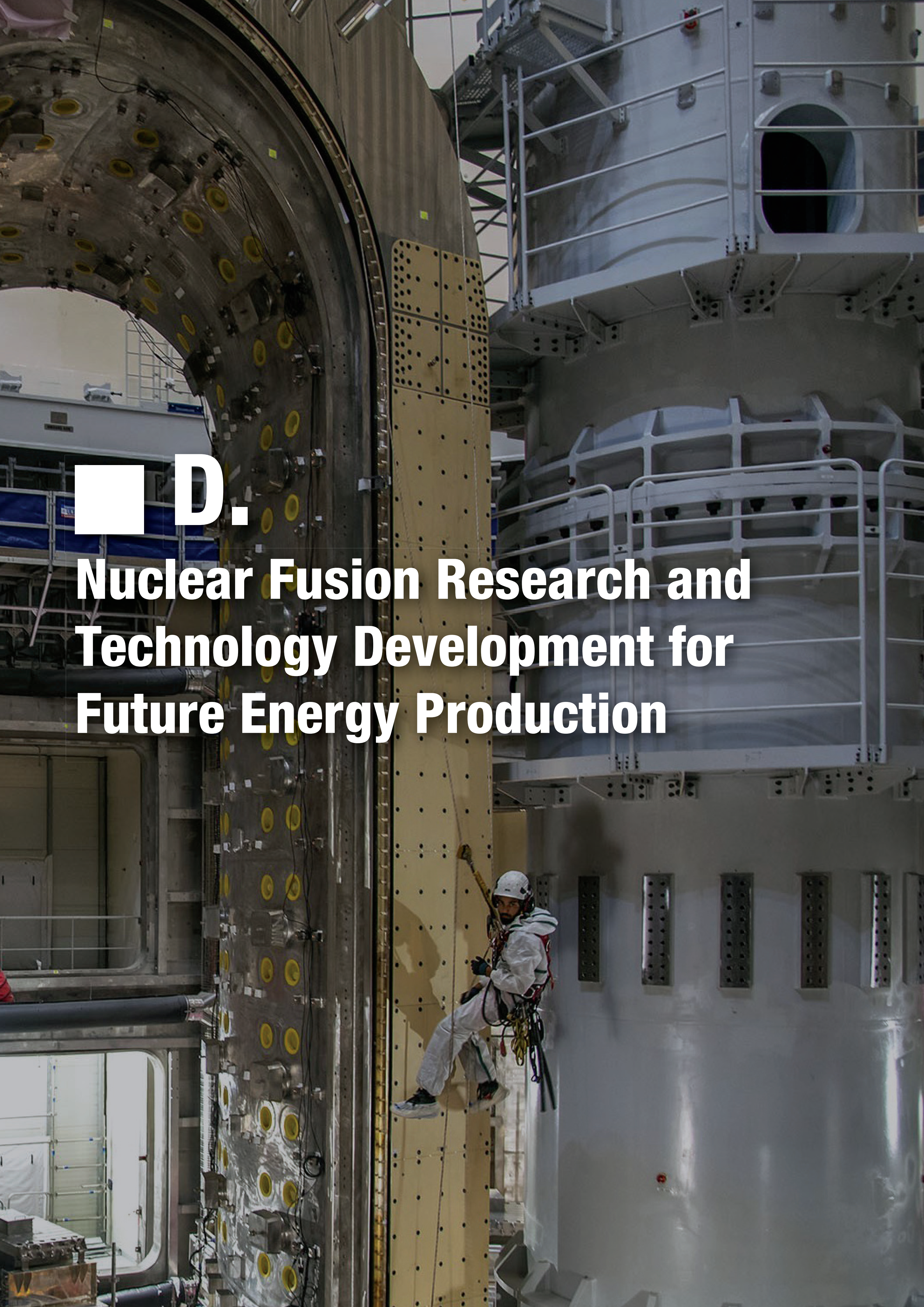
National policy and strategies for radioactive waste management continue to be initiated and refined in many Member States. For EU Member States, this is in line with the requirement to fulfil the obligations under Article 14.3 of Council Directive 2011/70/EURATOM of 19 July 2011.

There has been an increase in the return of disused high activity sources to suppliers for recycling and disposal. Over 30 high activity sources are planned to be removed from almost a dozen Member States in 2023. While many countries have made progress with respect to the management of disused sealed radioactive sources (DSRSs), disposal of DSRSs is still a challenge, especially in countries with smaller nuclear programmes. Malaysia is projected to finalize the first borehole disposal of DSRSs in 2023. This project is observed with great interest by many Member States whose inventories consist mainly of DSRSs. Bulgaria, Georgia and Ghana, among others, are considering this disposal technology.

Minimization of radioactive waste continues to be a priority. Thermal technologies and supercompaction continue to be the worldwide industry standard for achieving significant volume reduction of solid LILW. Use of geopolymers is currently being extensively studied in Member States as an alternative to ordinary Portland cement. In France, Électricité de France and Veolia have developed a joint venture, Waste2Glass, to process waste other than high level waste into a stable and durable glass waste form. In the United Kingdom, the Harwell research site has partnered with Augean, a hazardous waste management company to adapt an ultra-high-pressure water jetting technology to decontaminate pipes from the research site, thereby allowing the pipes to be recycled instead of disposed of as radioactive waste.

Progress continues to be made on management of legacy waste inventories. At the Hanford Site in the United States of America, large-scale treatment of radiochemical waste has begun for the first time. Well over 50 million gallons of waste have been generated since the 1950s and are currently stored in underground storage tanks pending final disposition. The Netherlands is building a new multifunctional storage building facility to store historical radioactive waste arising from medical isotope production. The facility will provide storage capacity through 2050. In the United Kingdom, operations have commenced on a 20-year programme to move magnesium swarf waste produced from the processing of Magnox fuel from six-metre-deep silos to purpose-built stainless steel waste containers for transfer to a modern storage facility.

As regards international collaboration in the field of radioactive waste management, a memorandum of cooperation between ČEZ of the Czech Republic and the Nuclear and Decommissioning Company of Slovakia was signed to share expertise in waste minimization and ageing management. The ERDO Association or Multinational Radioactive Waste Solutions continued its efforts towards finding multinational solutions for Member States with small inventories of long lived LILW. The European Joint Programme on Radioactive Waste Management continued to involve the participants in developing collaboration towards safe radioactive waste management. The EU's Implementing Geological Disposal of Radioactive Waste Technology Platform continues to actively pursue its Vision 2025 Report on having the first geological disposal facilities for spent fuel, high level waste and other long lived radioactive waste operating safely in Europe by 2025.



■ D.

Nuclear Fusion Research and Technology Development for Future Energy Production

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

Status

There has been good progress in the ITER project (Figure D.1). In June 2022, the project reached the milestone of 77% completion. The first vacuum vessel sector sub-assembly, which incorporates two associated toroidal field coils and thermal shield elements, has been completed and installed in the tokamak pit; and the third vacuum vessel sector has been delivered to the ITER site. With the completion of the cryostat top lid, all elements of the cryostat are now complete. Major progress has been achieved on plant systems: the cooling water system has been delivered and ready for commissioning; construction of the cryogenics plant has been completed, and the plant is now in functional testing; and 100% of the equipment needed for first plasma has been installed in the magnet power conversion buildings. On the other hand, recent results from analysis of ITER's first-of-a-kind key components indicated the need for extensive repairs. In addition, the ITER Organization has been addressing regulatory questions from France's Nuclear Safety Authority.

The impressive increase progress continued in setting up the consortium for the construction of the International Fusion Materials Irradiation Facility (IFMIF) DEMO Oriented Neutron Source in Spain, a facility critical for fusion materials development and validation. Planning for the project has been completed, and funding to cover construction costs is being secured. Similarly, the IFMIF Engineering Validation and Engineering Design Activities project in Japan

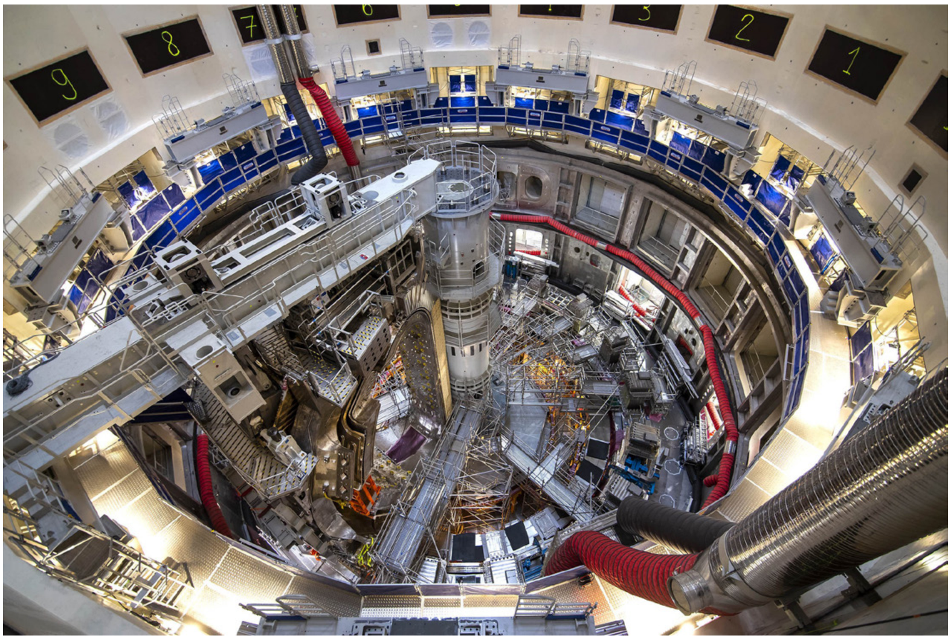


FIG. D.1. In the heart of the ITER Tokamak Building. This 30-metre-deep pit is the stage for ITER machine assembly. Assembly is progressing from bottom to top. (Photo: ITER Organization) continued to make progress in the integrated engineering design of the IFMIF and in the collection of the data necessary for decisions on the construction, operation, exploitation and decommissioning of the future fusion neutron source by completing the engineering validation activities of its three main facilities: the Test Facility, the Lithium Target Facility and the Accelerator Facility.

Commissioning of the JT-60SA tokamak in Japan, which started in April 2020, was interrupted due to insufficient voltage insulation capability in one of the magnetic coils. Improvement for isolation capability is ongoing, and commissioning is expected to restart later in 2023.

In October 2022, Wendelstein 7-X (W7-X) — the world's most advanced stellarator, located in Germany — entered its second experimental phase (Figure D.2). W7-X has now been fully equipped with a water cooled set of plasma facing components, allowing discharges of up to 30 minutes at 10 MW of heating, which should enable the achievement continuous operation.

A study[1] published in September 2022 reported that experiments at the Korea Superconducting Tokamak Advanced Research (KSTAR) facility in the Republic of Korea had produced a plasma fusion regime satisfying power plant performance requirements, including a high temperature above 100 million kelvin and sufficient control of instabilities to ensure steady state operation for tens of seconds. These results enhanced confidence in the tokamak design as a promising path towards commercial fusion power plants.

On 13 December 2022, the US Department of Energy announced the achievement of a historic scientific breakthrough for fusion energy. Researchers at the National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory (LLNL), were able to produce about 3.15 megajoules of fusion energy from a total of 2.05 megajoules provided by 192 laser beams, thus achieving an energy gain in the target of about 1.5 for the first time in a fusion experiment. The energy required to power the laser beams amounted to approximately 300 megajoules.

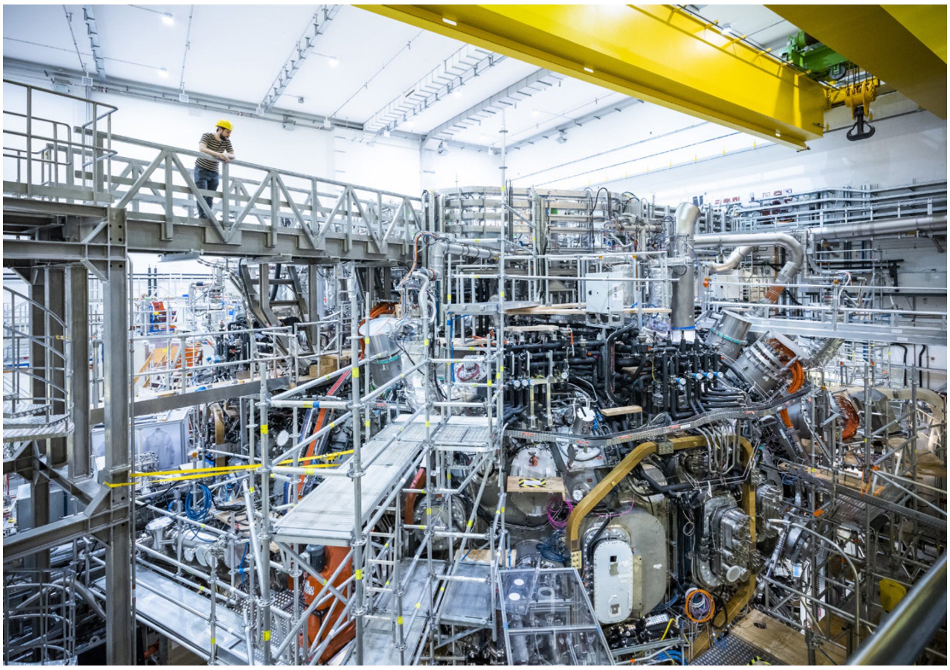


FIG. D.2. With doubled heating capacity, 40 new diagnostics and 6.8 kilometres of cooling pipes, the W7-X stellarator has started its second scientific experimental campaign. (Photo: Max Planck Institute for Plasma Physics)

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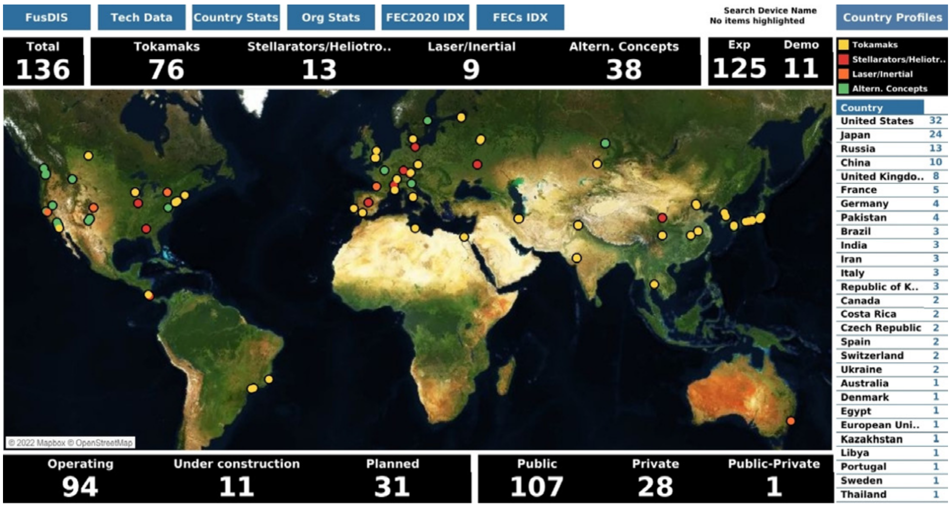
[1] Han, H., Park, S.J., Sung, C. et al. A sustained high-temperature fusion plasma regime facilitated by fast ions. Nature 609, 269–275 (2022). https://doi.org/10.1038/s41586-022-05008-1.

Demonstration fusion power plant (DEMO) concepts, the aim of which is to demonstrate net electrical gain from fusion, continue to be under development by individual governments, private companies and some public–private joint ventures (Figure D.3). At least 11 DEMO concepts are at various stages of development in China, European Union, Japan, the Republic of Korea, the Russian Federation, the United Kingdom and the United States of America, with target completion dates ranging between 2025 and 2055. In Italy, progress continued in the construction of the Divertor Tokamak Test (DTT) facility, a new superconducting tokamak devoted to the study of advanced divertor solutions for DEMO.



Total	Tokamaks	Stellarators/Heliotro..	Laser/Inertial	Altern. Concepts	Exp	Demo
136	76	13	9	38	125	11

Operating	Under construction	Planned	Public	Private	Public-Private
94	11	31	107	28	1

Country	
United States	32
Japan	24
Russia	13
China	10
United Kingdo..	8
France	5
Germany	4
Pakistan	4
Brazil	3
India	3
Iran	3
Italy	3
Republic of K..	3
Canada	2
Costa Rica	2
Czech Republic	2
Spain	2
Switzerland	2
Ukraine	2
Australia	1
Denmark	1
Egypt	1
European Uni..	1
Kazakhstan	1
Libya	1
Portugal	1
Sweden	1
Thailand	1

FIG. D.3. Over 130 experimental, public and private fusion devices are operating, under construction or being planned, while a number of organizations are considering designs for demonstration fusion power plants. (Source: Fusion Device Information System, IAEA)

In October 2022, the United Kingdom Government announced the location — a coal power station site in West Burton, Nottinghamshire — of its DEMO-type programme, “Spherical Tokamak for Energy Production” (STEP), which is targeted for completion by 2040 and aims to demonstrate the ability to generate net electricity from fusion and produce tritium as its own fuel.

Also in October of 2022, General Atomics in the United States of America announced plans for a steady state, compact advanced tokamak fusion pilot plant (Figure D.4). The design approach will rely on advanced sensors, control algorithms and high-performance computers for controlling the plasma, silicon carbide breeding blankets for producing the tritium and microwave heating necessary to power the fusion reactions.

The impressive increase in private sector investments continued in 2022. Private sector companies have declared that they have attracted around US $5 billion in total, and more than US $3 billion since June 2021. As of 2022, there are 33 such companies located in different parts of the world, namely in Australia, Canada, China, France, Germany, Israel, Italy, Japan, the United Kingdom and the United States of America (over 70% are in the United States of America alone).

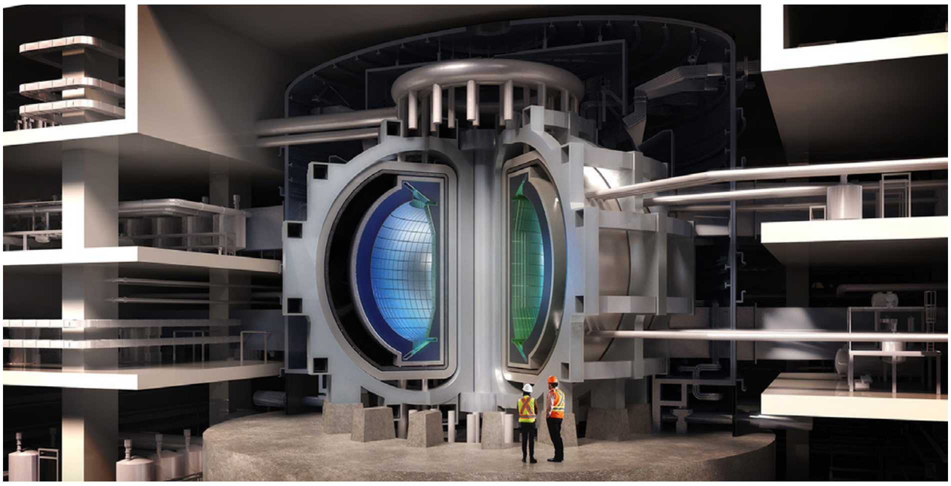


FIG. D.4. A rendering of the interior of the General Atomics fusion pilot plant. (Source: General Atomics)

Trends

In the United States of America, the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy, held in March 2022, launched three new initiatives, including a new Department of Energy (DOE) agency-wide fusion initiative, with a new lead coordinator for fusion energy joining the DOE Office of the Under Secretary for Science and Innovation. A common theme among these initiatives was the recognition that public–private partnerships present an opportunity to accelerate the research, development and demonstration (RD&D) of fusion energy. As a result, a funding opportunity announcement launched in September 2022 by the DOE Office of Science invited applications for a new milestone-based fusion development programme in partnership with the private sector towards the successful design of a fusion pilot plant.

AI-based modelling of plasma dynamics and real-time control of fusion experiments have seen huge improvements in their efficacy, offering an accelerated path towards fusion energy. One example is a study published in 2022 that showed how AI-based control systems were able to create and maintain a wide range of plasma shapes and configurations in the TCV tokamak in Switzerland by manipulating the 19 magnetic coils inside the device (Figure D.5). As part of a recently launched coordinated research project (CRP), the

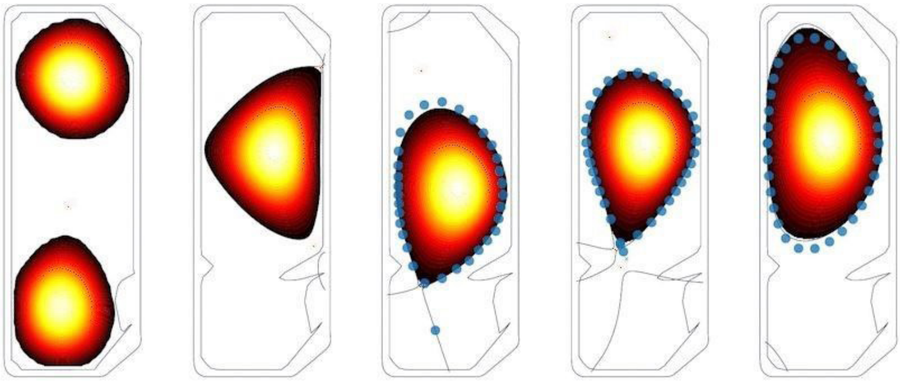


FIG. D.5. Range of different plasma shapes and configurations generated with the AI-based system controller. From left to right: droplets, negative triangularity, ITER-like shape, snowflake, elongated plasma. (Source: DeepMind, and the Swiss Plasma Center of the Swiss Federal Institute of Technology Lausanne)

Agency and its partners have developed use cases and benchmarking, and collected associated data for testing AI applications in fusion science at an international level.

In addition to the experimental science, Member States are accelerating technology development with its emergence in the private sector, with the subsequent significant increase in capital invested and recent breakthroughs, as well as the progress of large-scale international and national fusion projects. In this context, several Member States are considering options for a suitable national safety framework for fusion systems. The existing design safety standards and guidance for nuclear installations such as NPPs or accelerators do not cater for the specificities associated with fusion power plants, nor do they consider the potential hazards thereof.

Currently, around ten Member States regulate different experimental fusion facilities. In general, the operation of such facilities results in very limited amounts of radioactive materials for the purposes of demonstrating the viability of the concepts proposed. Member States are applying and, if necessary, adapting existing authorization and oversight requirements from either radiation protection or nuclear facility/installation frameworks to accommodate early R&D for future commercial fusion facilities. This approach is only feasible in the near term, and further developments in this area are required for the future.

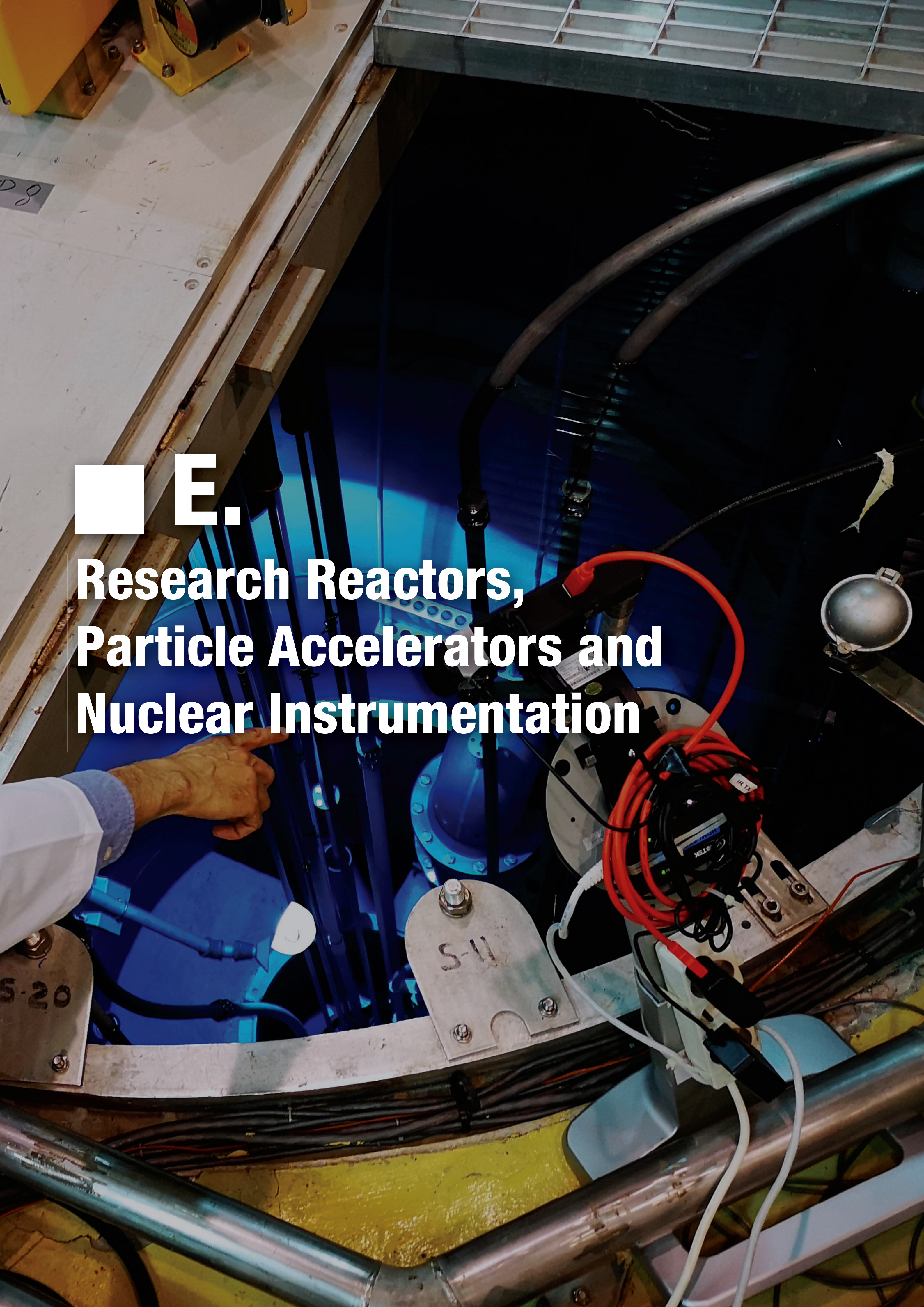
Many countries have acknowledged that updated or new national frameworks will need to be established to accommodate the additional complexities of commercial fusion facilities. Such complexities could include the use or generation of larger inventories of radioactive materials and extreme operating conditions (e.g. high temperatures, vacuum conditions and liquid metal coolant technologies), with a need to develop new materials. Furthermore, fusion presents different levels of hazards and associated risks when compared to fission processes and therefore might require a dedicated regulatory framework. Expectations for risk control and the approach of the regulator may also differ.

70 years’ experience in nuclear fission reactors can potentially help developing fusion technology for energy production by creating a synergy on technology development between nuclear fission and fusion.

The development of an adequate legal, institutional and regulatory national framework for fusion is intrinsically connected to the development of this new type of technology and its future commercial deployment. It is well understood that global harmonization in this area would support and accelerate the rise of a global fusion industry.

■ E.

Research Reactors, Particle Accelerators and Nuclear Instrumentation



E.

Research Reactors, Particle Accelerators and Nuclear Instrumentation

E.1.

Research Reactors

Status

There were 233 operational research reactors, including those in temporary shutdown, in 53 countries at the end of 2022. They continued to provide neutron beams and indispensable irradiation services for science, medicine and industry, and to contribute to education and training. The most frequent applications of research reactors are shown in Table E-1 in the Annex.

233 operational research reactors in

53 countries at the end of 2022

Eleven new research reactors, including one subcritical assembly and one accelerator driven system, are under construction in ten countries: Argentina, the Plurinational State of Bolivia, Brazil, China, the Czech Republic, France, the Republic of Korea, the Russian Federation, Saudi Arabia and Ukraine. Fourteen Member States have formal plans to construct new research reactors: Bangladesh, Belarus, Belgium, China, India, the Netherlands, Nigeria, the Philippines, South Africa, Tajikistan, Thailand, the United States of America, Viet Nam and Zambia. A significant number of countries are considering building research reactors, namely Azerbaijan, Ethiopia, Ghana, India, Iraq, Kenya, Malaysia, Mongolia, Myanmar, the Niger, the Philippines, Rwanda, Senegal, the Sudan, Tunisia and the United Republic of Tanzania.

International efforts continued to minimize high enriched uranium (HEU) use in the civilian sector. The IVG.1M reactor in Kazakhstan was converted to low enriched uranium (LEU) in 2022. In total, to date, 108 research reactors and major medical isotope production facilities have been converted from the use of HEU to LEU or confirmed as being shut down. All major global producers of molybdenum-99, the most demanded medical radioisotope, will be using non-HEU production methods by April 2023. In total, 6885 kilograms of HEU have been repatriated to their country of origin or otherwise dispositioned from 48 countries (and Taiwan, China).

11 new research reactors are under construction in **10** countries

14 Member States have formal plans to construct new research reactors

16 countries are considering building research reactors

Trends

The share of research reactors operating for at least 40 years is approaching 70%. Many operating organizations have, or are in the process of establishing, proactive strategies and systematic ageing management, refurbishment and modernization programmes to allow continuous safe operation for 60 years and beyond. Some organizations operating highly utilized research reactors are considering the extension of their active lifetime to 80 or even 100 years (Figure E.1). Screening of structures, systems and components in terms of their impact on safety and reliability of operation; identification and understanding of degradation mechanisms; detection, monitoring and mitigation of ageing effects are becoming commonly accepted elements of such programmes.

Many countries take advantage of opportunities to access research reactors through international and regional collaboration initiatives, such as International Centres based on Research Reactors and Internet Reactor Laboratories.

After some reduction in activity owing to the COVID-19 pandemic, Member States are stepping up their efforts to increase utilization of their operational

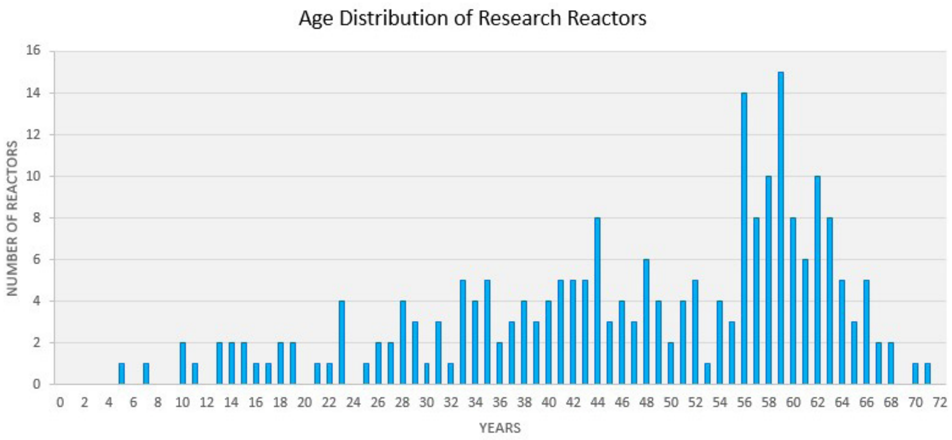


FIG. E.1. Age distribution of operational research reactors, November 2022. (Source: IAEA Research Reactor Database) research reactors. While a return to pre-pandemic levels of radioisotope production has resulted in the normalization of demand and the re-establishment of critical logistics and supply lines, expansion of other applications requires careful consideration of the potential for growth and the constraints that may limit that potential. For instance, current developments in neutron radiography at zero or low power research reactors and neutron generators have opened new possibilities for the expansion of the application of this technique, which is used, inter alia, for R&D, cultural heritage studies and industrial applications. Low-cost, high-quality systems, initially developed at the Heinz Maier-Leibnitz Research Neutron Source in Germany, have now been implemented at other facilities. Three-dimensional tomographic images have been obtained thanks to the newly built neutron imaging system of the VR-1 reactor of the Czech Technical University in Prague (Figure E.2). The reactor operates at 500 watts, a power lower than what was previously considered possible for neutron tomography. A similar system has been installed at the RECH-1 research reactor in Chile, while another was successfully tested at the Agency's newly established Neutron Science Facility in Seibersdorf, which is based on compact deuterium–deuterium and deuterium–tritium neutron generators.

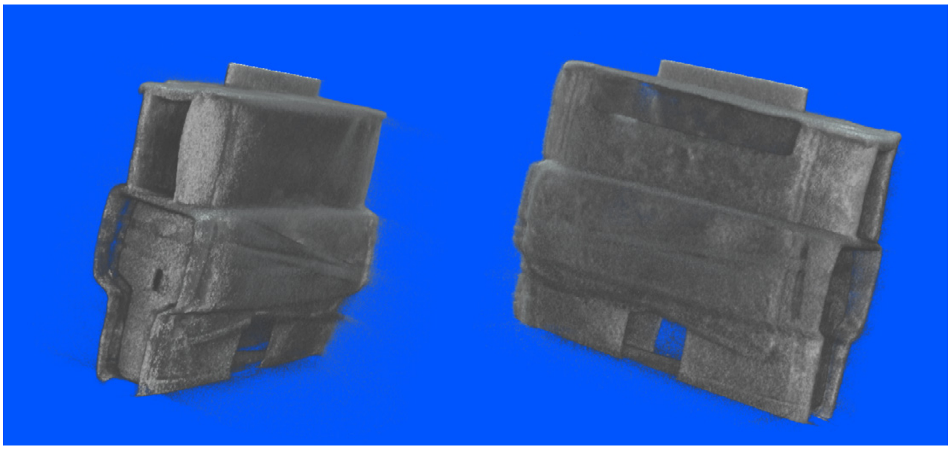


FIG. E.2. Two cross sections from a tomography of an ancient Tibetan lock taken at the 500-watt VR-1 reactor of the Czech Technical University in Prague.
(Image: Czech Technical University in Prague, Czech Republic; Heinz Maier-Leibnitz Centre, Technical University of Munich, Germany)

E.2. Particle Accelerators

Status

Boron neutron capture therapy (BNCT) is a novel cancer therapy combining the use of a tumour-seeking boron pharmaceutical and an external neutron beam. Interest in BNCT has continued to grow around the world, in particular following the approval in Japan of BNCT at accelerator-based facilities as a routine clinical treatment for recurrent, non-resectable head and neck cancer (Figure E.3). Other countries have facilities that are now in an advanced stage of development towards routine clinical treatment, such as in Helsinki, Finland and Xiamen, China, and new accelerator-based projects were announced in 2022, including a second facility in China, in Hainan province, and a facility in Brussels, Belgium. There are now more than 20 accelerator-based BNCT facilities in 11 Member States in various stages from planning to routine operation, and several companies are offering commercial solutions for the accelerator, neutron production targets and moderation components, treatment planning and patient

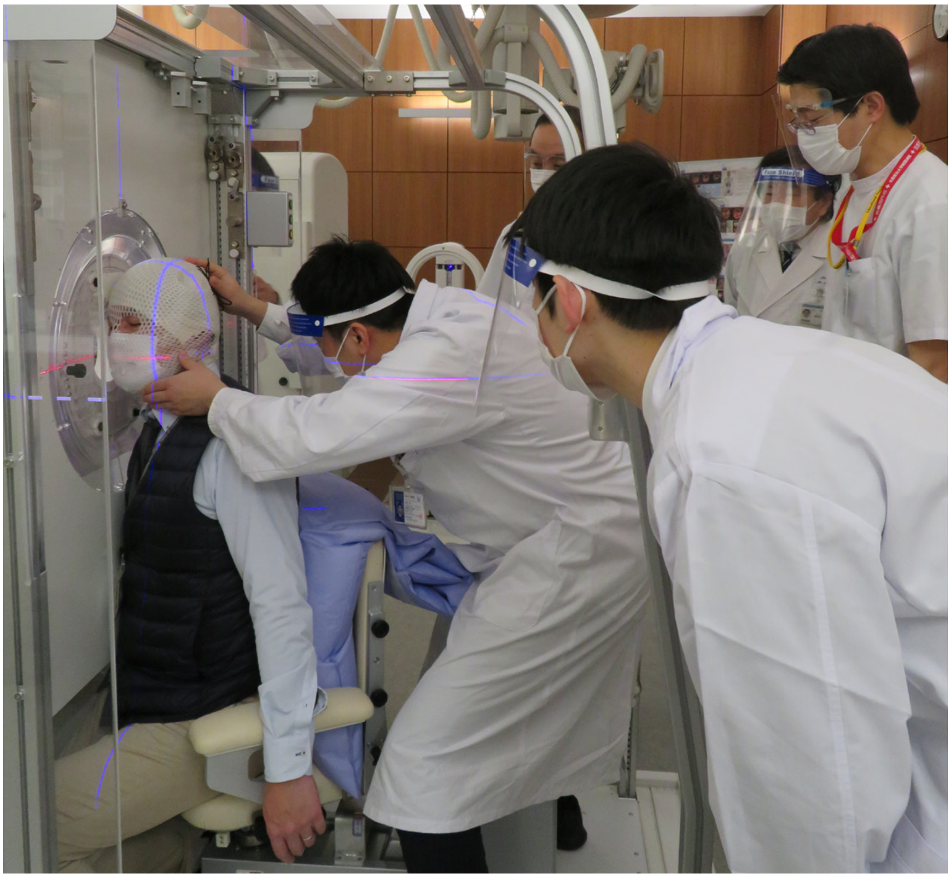


FIG. E.3. A student acts as a patient being aligned in preparation for BNCT treatment at a recent training course held at Kansai BNCT Medical Center, Japan.
(Photo: Kansai BNCT Medical Center)

positioning systems, and pharmaceuticals. In the area of outreach and capacity building, the International Society for Neutron Capture Therapy is very active and issues regular communications, and organizes an annual conference and events dedicated to the next generation of BNCT professionals.

Trends

One of the main industrial uses of low energy electron accelerators is the sterilization of medical products, including single use medical devices. Historically, the majority of radiation sterilization was performed using gamma sources, such as cobalt-60. However, owing to a limited supply chain and to safety and security concerns associated with the use and management of cobalt-60, many users are actively pursuing accelerator-based alternatives. Direct electron beam sterilization has been utilized for many years to efficiently treat low density products. In addition, equipping electron accelerators with an electron to X-ray converter enables the generation of sufficient intensity of X-ray flux for other industrial uses. While this is a relatively high energy consuming solution, it combines the advantages of accelerators (high dose rate and correspondingly high product throughput) and gamma sources (deep product penetration).

Development of more powerful and reliable electron accelerators remains the main goal of the user community and several technology providers worldwide are actively working in this field. Existing devices are in high demand and accelerator producers are working at full capacity to satisfy the growing interest. Nowadays, many companies offer a complete solution (electron accelerator, X-ray conversion target, shielding structures, conveyor, process control systems, etc.), which can often be tailored to customer needs, for example to maximize throughput or process delicate products, or to provide greater versatility. All these ongoing efforts are gradually changing the landscape of irradiation technologies, with a resulting increase in the share of products and services offered by accelerators.

E.3. Nuclear Instrumentation

Status

AI and its derivatives continue to be involved in more and broader applications in nuclear instrumentation. Recently, it has been introduced in mixed field radiation detection for discrimination of pulses produced by different particles. A typical example is the discrimination between photon and neutron signals in plastic scintillators. Classification algorithms are applied to successfully discriminate pulses after they have been processed.

On a similar scientific front, life sciences already benefit from AI applications. Deciphering protein folding structures with X-ray or neutron crystallography in 3D is a long-standing scientific problem. In addition to the advanced detection instrumentation that is becoming available, the AI community, including private vendors, has focused its efforts on deep learning algorithms that successfully predict protein structures. Recently, deep learning software developments in combination with publicly available tools have made waves in our understanding of the human proteome folding down to atomic distances, and these developments are expected to lead to break-through discoveries in the coming years.

Trends

Larger-scale AI applications have been revolutionizing the world of high-energy physics. As hadron accelerators are being upgraded to higher luminosities, the number of particles produced per collision is increasing. As a consequence, tracking detectors need to operate at higher counting rates, potentially with higher background counts, as rare probe discovery channels are targeted. The respective reconstruction algorithms need to tackle a higher payload of detector hits, clusters and tracks. The particle physics community has introduced the use of ML algorithms to optimize and accelerate track reconstruction, as well as to minimize background contributions from track misidentification. The community has also organized open competitions where participants are invited to enter their algorithms to address the high luminosity regime of the super Large Hadron Collider. An optimization in this regard becomes even more significant as detectors enter the era of triggerless read-out. As in the past, much of these innovations in particle physics also have a great potential to be applied in advanced nuclear instrumentation.

The trend in using uncrewed aerial vehicles (UAVs) for radiation detection and surveillance is currently influenced by new parameters towards higher payload, safety and flight durability, resistance and guidance accuracy. New commercially available UAVs for radiation detection and gamma spectrometry have emerged, offering a comprehensive solution for radiological mapping. Robotic containers are being developed for UAV autonomous operation, and remote missions allow for unattended take-off and landing, charging or battery replacement, weather protection and more. Thanks to the ever-increasing accuracy of global navigation satellite systems, surveys have started to focus more on precise scanning of smaller objects such as port loading docks, containers or buildings.

The use of silicon photomultiplier-based radiation detectors has improved performance and compactness. Built-in electronics for temperature compensation and read-out electronics play an important role for implementation into UAV technology. Detectors such as plastic scintillators, GAGG detectors, as well as detectors enabling gamma and neutron detection based on ZnS(Ag)/6LiF or CLYC and CLLB are appearing in UAV-based systems.

The application of plastic scintillation detectors seems to be a new trend. The plastic is promising in terms of low specific weight (density around 1g/cm3), various shapes and high detection sensitivity. Existing spectrum processing algorithms allow plastic detectors to distinguish between artificial and NORM isotopes, or to identify basic, especially industrial, radionuclides.

New approaches to real-time data processing and post processing have also been introduced for optimizing the time taken by UAVs to accomplish radiation detection missions. For example, combinations of a radiation sensor with light detection and ranging (LIDAR) are available, enabling high-resolution 3D gamma imaging in real time or dual gamma-ray and neutron mapping with neutron/gamma discrimination. The use of a high-resolution camera for 3D photogrammetry or LIDAR allows for the application of algebraic reconstruction techniques to correct the distances of all contributing surfaces and for the detector response in 3D, as illustrated in Figure E.4.

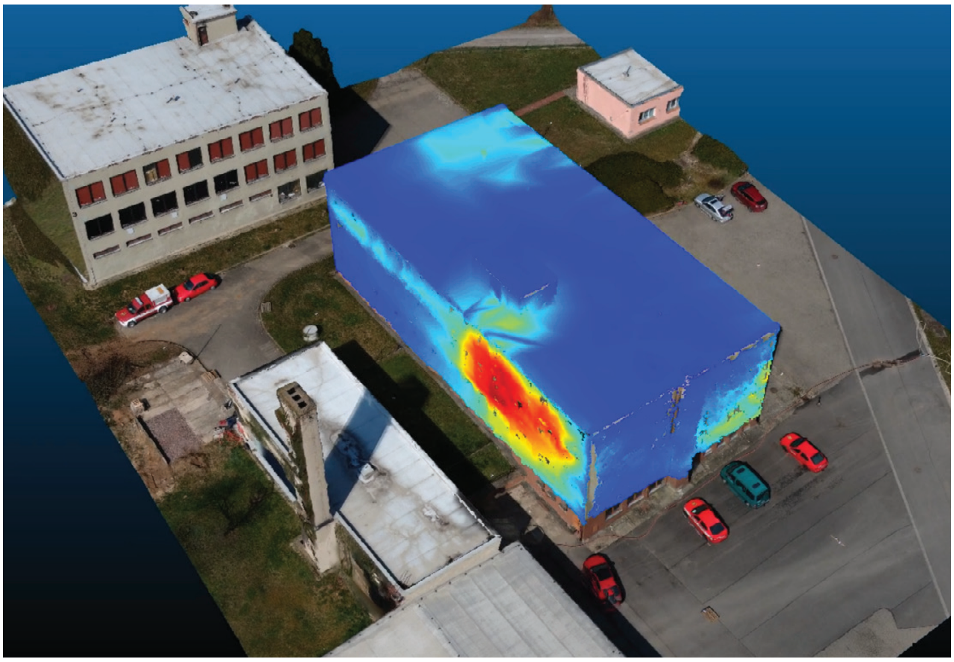


FIG. E.4. Example of UAV-based 3D radiological mapping of a building containing radioactive sources/material. (Graphic: IAEA)

F.

Food and Agriculture

F.
Food and Agriculture

F.1.
Rapid Response to Food Safety Crises

Status

Recent events, including the COVID-19 pandemic, conflicts and climate-related natural disasters, have highlighted the vulnerability of the worldwide food supply to stress situations, as well as the need to increase resilience by reforming food control systems and improving technical support. Crises and emergencies, such as extreme climate events, natural catastrophes, epidemics and pandemics, disrupt food safety control systems, compromise food safety and food security, and present opportunities for food adulteration and food crime. Strengthening the preparedness and rapid response capabilities of Member States is essential to tackling these challenges.

Food control systems generally rely on laboratory-based two-tier testing programmes. Cost-effective, high-throughput testing methods are used to screen products sampled under national regulatory food safety surveillance plans. Any results indicating possible contamination above regulatory tolerance levels are then verified using more sophisticated and time-consuming techniques. Nuclear techniques, such as isotope dilution mass spectrometry, and stable isotope ratio measurements, play an important role in this testing. To ensure that contaminated food does not remain in the food supply, the screening tests are biased towards the minimum possible number of false negative results (when contaminated food is not detected). However, owing to analytical method performance and measurement uncertainty, there may be false positive results (when uncontaminated food is erroneously classified as contaminated), which impact producers and the food industry. The second tier — confirmatory testing — positively identifies contamination with very few false positive results. This type of food control system protects both consumers and producers and helps enable trade.

Changing environmental conditions are altering natural toxin patterns in crop, livestock and fishery production. For example, changing climatic conditions promote the growth of mycotoxin-producing fungi in regions where they were previously not present and where producers did not need to consider such a threat. Rising temperatures, in combination with eutrophication, will likely increase the frequency and duration of cyanobacterial blooms in many aquatic ecosystems, as well as the bioaccumulation of methylmercury in commercial fish species, posing additional food safety risks (Figure F.1).

Climate change also affects the prevalence and distribution of pests and disease vectors, requiring altered use of pesticides and veterinary drugs. This may pose an additional risk if residues remain in food. The use of antimicrobial substances in farm animals has also been linked to antimicrobial resistance, which can lead to the development of resistant bacteria, potentially resulting in their transfer through contaminated food.

Each of these drivers, individually or in combination, can have drastic effects on the various components of the One Health approach, especially regarding the safety and integrity of food and feed supplies. These effects are exacerbated when normal control systems are disrupted, as demonstrated by the impact of the COVID-19 pandemic, despite the disease not being food-borne.

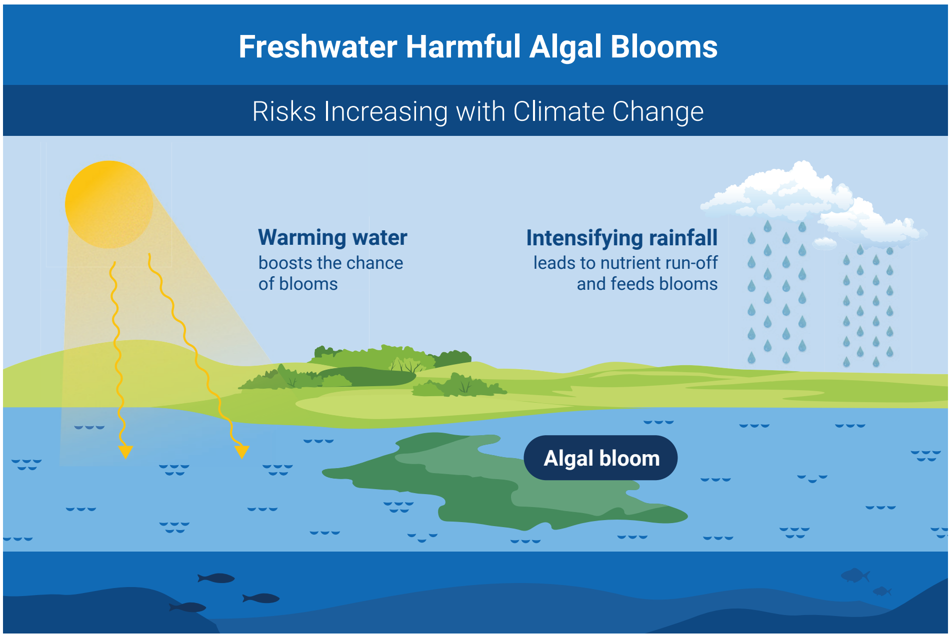


FIG. F.1. The risk of toxins in seafood owing to contamination from cyanobacterial blooms (harmful algal blooms) increases because of climate change. (Graphic: IAEA, based on www.climatecentral.org/climate-matters/harmful-algal-blooms)

Trends

In emergencies, when supply chains are disrupted and food control laboratories and systems are compromised or unavailable, the overriding priority is to ensure that the food supply remains safe. Protecting consumer health and preventing health services from facing further food safety problems helps prevent exacerbation of the crisis. Therefore, in crisis situations, the emphasis should be shifted to fast, easily implemented screening methods, in order to maintain food safety standards and determine or confirm the origins of contaminated foods. Available resources can then be targeted towards high-end techniques that provide information essential for crisis control and management.

Rapid food testing is supported by various nuclear and isotopic techniques, as well as measurements of isotopic composition, used either alone or in conjunction with complementary techniques. Nuclear analytical techniques depend on robust parameters, such as mass, spin, magnetic moment, energy levels of an atom’s nucleus and inner shell electrons, and isotopic measurements of elemental composition.

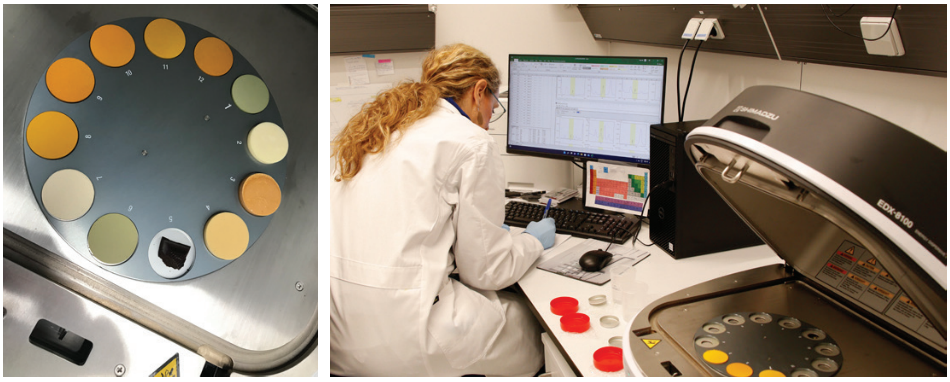


FIG. F.2. Analysis of turmeric samples using benchtop energy dispersive X-ray fluorescence to detect toxic elements at the Food Safety and Control Laboratory, Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, Seibersdorf, Austria. (Photo: IAEA)

Recent advances in semi-conductor, photonic and other technologies have enabled the miniaturization of analytical instruments, resulting in a variety of benchtop, hand-held, and portable devices that can be applied not only in the laboratory, but at various points throughout the food production and supply chains. These support rapid interventions in crises by providing information for decision making.

One example is the development of applications of energy dispersive X-ray fluorescence (EDXRF) for the rapid screening of food in order to detect elemental nutrients and toxic metals, such as lead, cadmium and arsenic, at regulatory levels set by the World Health Organization.[2] The technique is available in hand-held and benchtop (Figure F.2) formats and can be used in the field or on site by non-specialized operators. It requires minimal sample preparation and does not use environmentally harmful reagents. In combination with chemometric tools, the prediction performance of EDXRF can also be extended to food fraud issues.

Another example is gas chromatography–ion mobility spectrometry (GC–IMS), a technique that employs a low energy tritium hydride radiation source. Headspace–GC–IMS (Figure F.3) can be used to detect microbial volatile organic compound fingerprints, which indicate the presence of a fungus, providing advance warning of potential mycotoxin production in food and allowing control measures to be implemented[3]. GC–IMS can detect many other contaminants and hazard fingerprints in food, including methanol, a chemical that can be found in adulterated alcoholic beverages and has toxic metabolites when ingested, and ethylene oxide, a toxic pesticide that has been the cause of multiple recalls of contaminated food products in Europe since 2020.

These and other rapid nuclear analytical techniques, such as benchtop nuclear magnetic resonance spectroscopy and stable isotope analysis by cavity ring down spectroscopy, in combination with portable spectroscopic methods, such as surface-enhanced Raman spectroscopy and Fourier transform infrared spectroscopy, provide a suite of powerful analytical instruments. Applications of such tools for food analysis in the field, which will further enable effective response to emergencies or crises affecting the food supply, are rapidly developing.

FIG. F.3. Headspace–GC–IMS analysis to detect characteristic fingerprints of food contaminants, performed at the Food Safety and Control Laboratory, Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, Seibersdorf, Austria. (Photo: IAEA)

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[2] Byers, H.L., McHenry, L.J., Grundl, T.J., XRF techniques to quantify heavy metals in vegetables at low detection limits, Food Chemistry: X 1, Vol. 1 (2019).

[13] Wang, S., Mo, H., Xu, D., Hu, H., Hu, L., Shuai, L., Li, H., Determination of volatile organic compounds by HS–GC–IMS to detect different stages of Aspergillus flavus infection in Xiang Ling walnut, Food Science & Nutrition, Vol. 9, Issue 5 (2021).

F.2. Advances in Food Irradiation: Increased Machine Source Use and New Soft Beam Technology

Status

Food irradiation is a chemical-free way to improve food safety, maintain food quality and extend shelf life. Whether through gamma photons, electron beams, or X-rays, ionizing radiation is gentle on food, but tough on microbes and pests. Since irradiation does not cause a noticeable rise in food temperature, the controlled application of irradiation neither compromises nutritional quality nor significantly impacts the taste, texture or appearance of food. In conventional food irradiation, the beams are energetic and penetrating, meaning even pre-packed foods can be irradiated; the wrapping also protects the food from the risk of external contamination after treatment.

The irradiation of at least 1 type of food commodity is allowed in about 70 countries, and more than 160 irradiation facilities in some 50 countries routinely treat food (Figure F.4). Within the prevailing business model, commercial irradiation centres function as multipurpose service providers: they consistently deliver the certified dosage of ionizing radiation, within a predefined dose range, for a range of products in order to meet the needs of customers from sectors including medicine, pharmaceuticals, and food.

At present, almost all irradiated food products are processed at specialist facilities that use gamma rays from cobalt-60, a radioactive isotope that emits high energy photons at 1.17 and 1.33 megaelectronvolts (MeV). About 90% of commercial food irradiation facilities use gamma rays, while others utilize machine source irradiation, which produces electrically generated high energy electron beams (up to 10 MeV) and/or X-rays (usually up to 5 MeV, although some countries allow up to 7.5 MeV). About 5% of food irradiation service providers have invested in electron beam and X-ray machine source capacity, in addition to their cobalt-60 irradiation units. Diversity of technology is becoming increasingly important as the demand for cobalt sources continues to grow, and the production of cobalt-60 has a lead time of several years. The cobalt-60 radionuclide is becoming more and more expensive, making electron beam, and even X-ray, irradiation attractive alternatives, as well as rising interest in soft beam technology that uses machine sources (Figure F-5).

A good example of the utility of food irradiation is in the case of dried foods such as spices, in which many microbes, including food-borne pathogenic

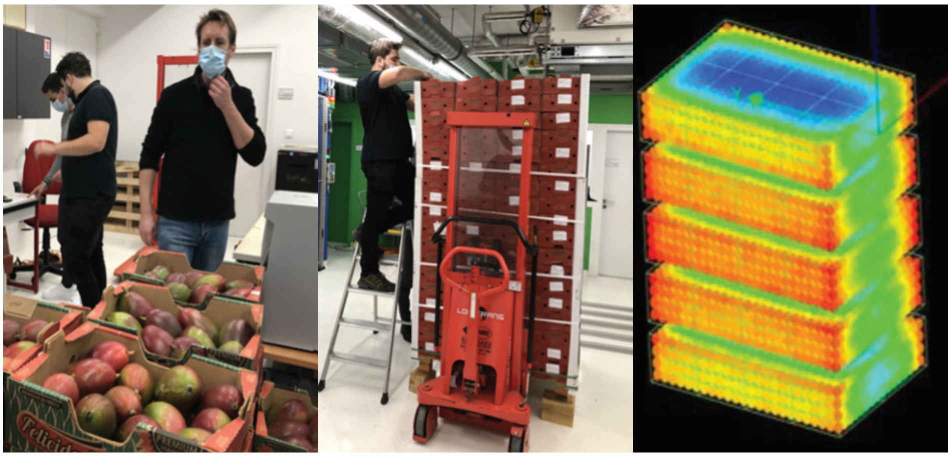

FIG. F.4. Experts at a food irradiation facility in France undertake tests to verify that X-ray irradiation of palletized mango fruits can achieve the minimum dose required for correct phytosanitary treatment (left and centre). The dose map illustrates the variation of absorbed dose (right). (Photos: Aerial, France)

FIG. F.5. Soft electron food processing equipment. The Laatu machine uses two low energy electron lamps (the red handles in the middle of the picture) to process dried ingredients as they fall through a stream of electrons. With a reduced energy consumption of up to 80% less than steam methods, it provides a cost efficient solution for microbial reduction. (Photo: Bühler)

microorganisms, such as salmonella, Bacillus cereus, and Clostridium perfringens, can survive in a dehydrated state.[4] Although contamination levels might be low, adding dried spices to food provides these microorganisms with both water and a rich environment in which they can rapidly multiply and thrive. Microbial reduction treatments are therefore necessary in order to minimize the risks of illness among consumers and trade loss owing to food spoilage. Thermal treatments, although effective, also remove the volatile components that give spices their unique flavours, vibrant colours and aromas, as well as their health-promoting attributes. In contrast, ionizing radiation destroys the above microbes, but has a minimal effect on the components within spices that are responsible for their sensory, quality and wellness attributes. Ionizing radiation can also slow down maturation, preventing foods such as garlic, ginger, onions and potatoes from sprouting.

Since it stops pests from developing and reproducing, ionizing radiation is also used as a phytosanitary treatment to enable trade across quarantine boundaries. For instance, it can ensure that economically significant pests, such as fruit flies and weevils, cannot spread and establish themselves in new territories through trade in fresh fruits and vegetables.

The Agency and the Food and Agriculture Organization of the United Nations (FAO) have been helping Member States (Figure F-6) to establish and expand food irradiation services, reducing food loss and waste and facilitating trade of dried spices and both fresh and frozen seafood and fruits. A recent example is Viet Nam's securement of fresh mango, dragon fruit and lychee exports to the United States of America worth US $20 million annually and its expanding trade with Australia.

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[4] *Microbiological hazards in spices and dried aromatic herbs: Meeting report* (Microbiological Risk Assessment Series No. 27, FAO/WHO, Rome, 2022).

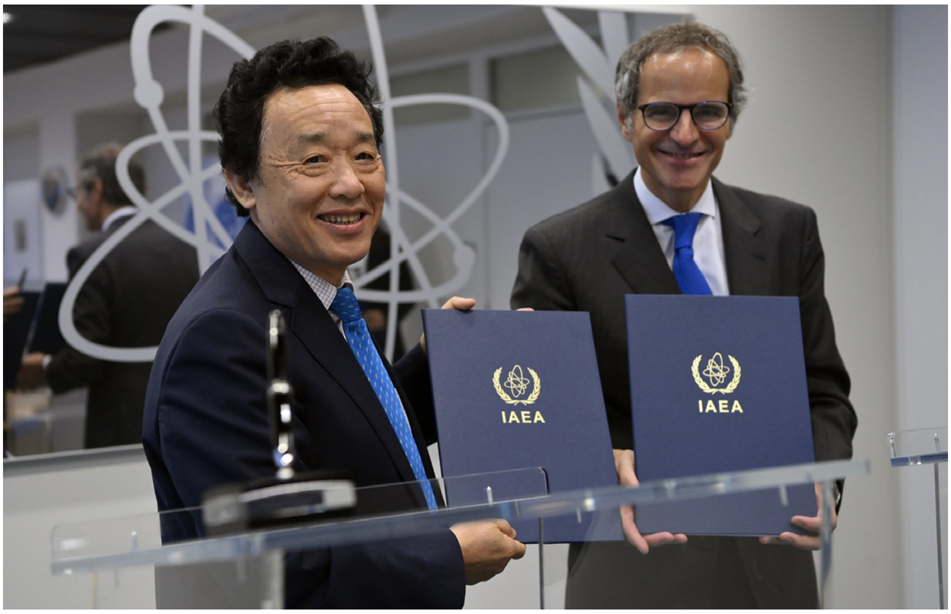

FIG. F.6. On 31 October 2022, IAEA Director General Rafael Mariano Grossi and FAO Director General Qu Dongyu signed a Memorandum of Understanding between the two organizations on Strengthening FAO/IAEA Cooperation in the Area of the Peaceful Application of Nuclear Technology in Food and Agriculture at the Agency headquarters in Vienna, Austria. (Photo: IAEA)

Trends

A notable trend is the expansion of machine source irradiation. The 'rise of the machine' is due to both its economic and practical advantages. In contrast to gamma irradiation, machine sources of ionizing radiation can be turned on and off, emitting beams of radiation as desired. In this way, they avoid the procurement, safety and security (transport, storage and disposal) issues associated with radioisotopes. Although gamma irradiation is a simple, reliable and mature technology that will be available for many years to come, alternative technologies help complement the available capacity and enable the wider use of food irradiation.

The Agency has supported Member States in their efforts to develop novel and practical applications of machine source food irradiation through coordinated research.[5] New advances in the field include the development of tools that can simulate the food irradiation process and rapidly ascertain optimum treatment parameters. Institutions in China and Viet Nam have designed, built, tested and installed new devices that are helping commercial high energy electron beam irradiation centres to model and calculate dose distributions for different loading configurations. These devices enable the optimum settings to be determined in advance, allowing for rapid testing at facilities and ultimately reducing beam downtime and improving productivity. Experts at Tsinghua University, China, have taken the concept further by working with technology company NUCTECH to develop a commercial product.[6] These, as well as similar tools in development elsewhere, are aimed at facilitating good practices and enhancing productivity at gamma and X-ray irradiation facilities, as well as at electron beam facilities.

Research at Texas A&M University, United States of America, an Agency Collaborating Centre, is focusing on efficient and rapid methods to estimate the decimal reduction dose (D10) for pathogenic microorganisms in a range of different environments. The D10 is the dose of radiation needed to inactivate

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[5] *Development of Electron Beam and X Ray Applications for Food Irradiation: Final Report of a Coordinated Research Project* (IAEA-TECDOC-2008, Vienna, 2022).

[6] Qin H., Yang, G., Kuang, S., Wang, Q., Liu, J., Zhang, X., Li C., Han, Z., Li, Y., Concept development of X-ray mass thickness detection for irradiated items upon electron beam irradiation processing, Radiation Physics and Chemistry, Vol. 143 (2018) 8–13.

90% of an initial viable microbial population. An effective sterilizing irradiation dose can be calculated as a multiple of the D10. The Agency-funded research at Texas A&M University is an example of how applied research can take on new directions in response to changing needs, in this case the need to enhance techniques that help to avoid the transfer of pathogens via food, and thus prevent food-borne pandemics.

An interesting trend in the development of irradiation technologies is related to the ability to alter and tune beam energy in machine source devices. For instance, low energy beams (soft electrons or soft X-rays), with energies measured in kiloelectronvolts (keV), can be used in relatively compact irradiation lamps that can be safely housed in cabinets or other devices. This makes it feasible to bring food irradiation into the factory, as such soft beam devices can be fitted into food production lines. Since they cannot pass through the whole bulk of a food, soft electrons can effectively treat items in which microorganisms are found mainly on or near food surfaces, such as whole shell eggs (Figures F.7 and F.8), raw whole cuts of meat and poultry, and whole dried seeds (herbs and spices). Soft X-rays can also be used when the beam needs to pass through small batches of a food.

Research indicates that soft electrons can improve the quality of some foods, as well as being a promising method of surface and near-surface microbiological decontamination. For example, food engineering company Bühler has developed a free fall system to pass dried ingredients through a soft electron beam (<300 keV), a method that ensures the control and maintenance of microbiological contamination at acceptable levels.[7,8] An example of the development of soft X-ray irradiation for small batches is the case of a cabinet irradiator, generally used to sterilize medical instruments, which researchers at the Advanced Radiation Technology Institute of the Korea Atomic Energy Research Institute investigated as a means of processing food. The researchers' aim was to use a soft beam technology that is readily available in hospitals to provide food of a very high hygienic standard for immunocompromised patients, and this low energy (160 keV) X-ray technology has proven capable of ensuring that fresh cut vegetables meet that standard.

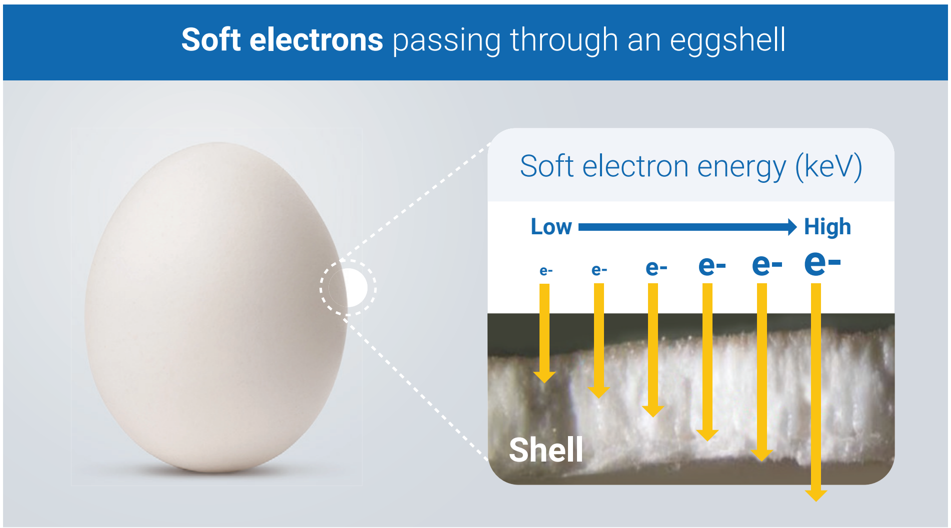
Soft electrons passing through an eggshell

FIG. F.7 Concept demonstrating the use of soft electrons (e-) with different energies to penetrate an eggshell to different depths. The aim is to ensure the electrons can destroy salmonella that resides mainly on or near the shell surface of fresh whole eggs. (Graphic: IAEA, based on the work of N. Takaoka, Tokyo Metropolitan Industrial Technology Research Institute, Japan).

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[7] *Laatu: Non-thermal, in-plant microbial reduction solution for dry foods* (Bühler, 2019).

[6] Schottroff, F., Lasarus, T., Stupak, M., Hajslova, J., Fauster, T., Jäger, H., Decontamination of herbs and spices by gamma irradiation and low-energy electron beam treatments and influence on product characteristics upon storage, Journal of Radiation Research and Applied Sciences, Vol. 14 1 (2021) 380–395.

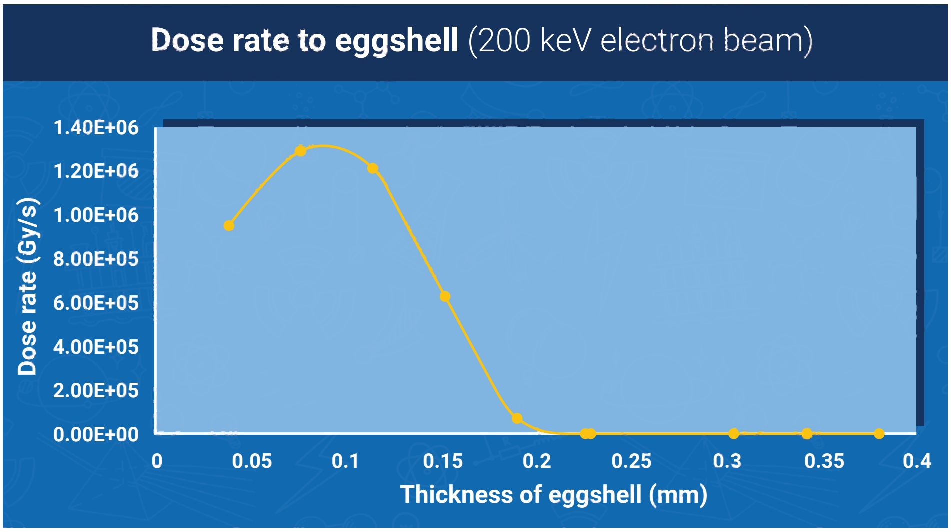
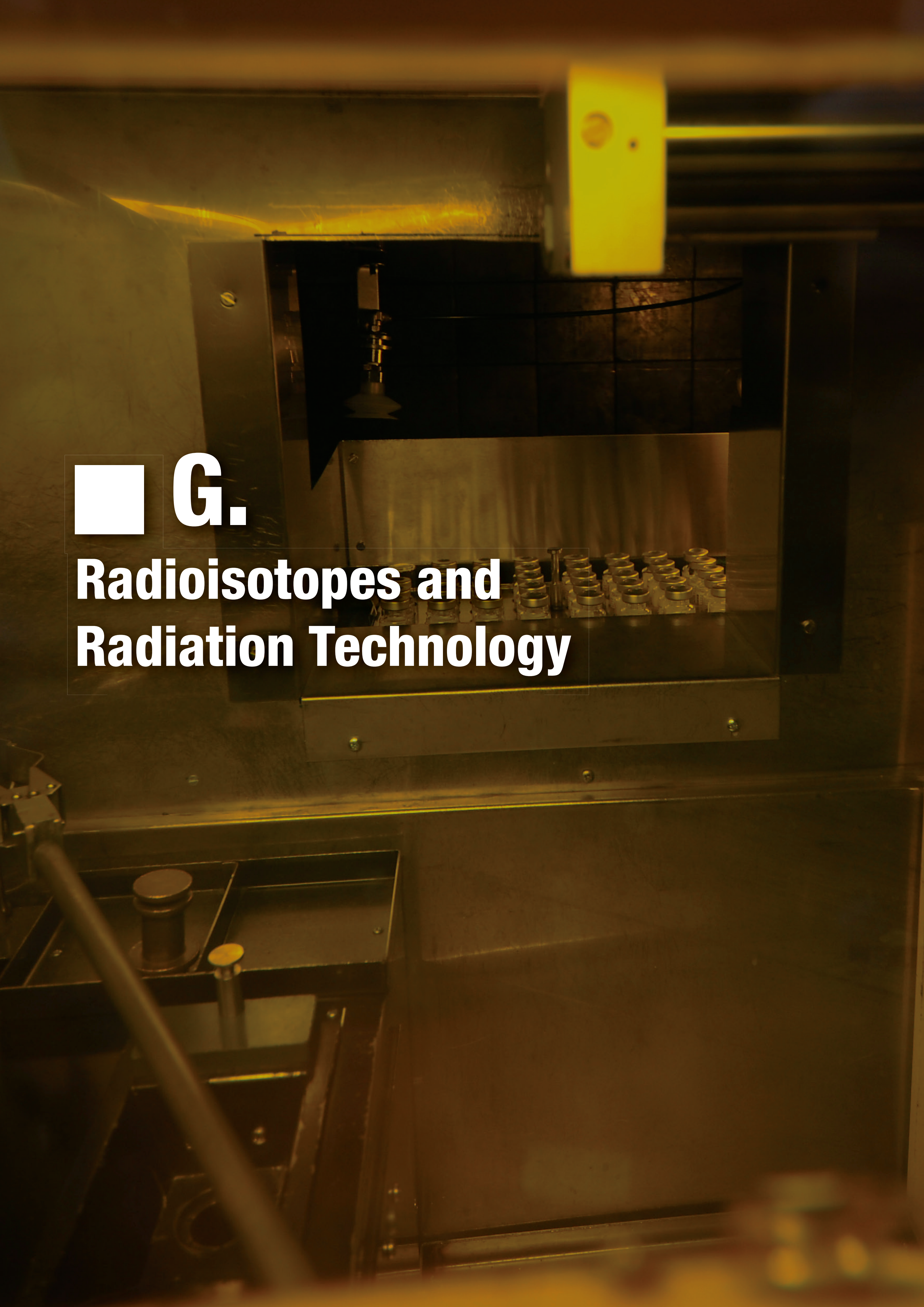


FIG. F.8. Simulation modelling to estimate the range of 200 keV soft electrons in eggshells and determine the feasibility of targeting salmonella at a depth of less than 0.2 mm. (Graphic: IAEA, based on the work of Y. Liu, H. Qin, H. Shi of NUCTECH Ltd. and H. Zhang of Tsinghua University, China)

An Agency coordinated research project on innovating machine source food irradiation with low energy beams is currently under way, with a focus on addressing technical challenges and growing the potential of new soft beam technologies. Countries involved in technical cooperation projects in the Africa and Asia and the Pacific regions have already expressed an interest in, and desire for, the commercial viability of soft beam irradiation worldwide



G.

Radioisotopes and Radiation Technology

G. Radioisotopes and Radiation Technology

G.1. Developments in Theranostic Radiopharmaceuticals

Status

Theranostic agents combine a radionuclide for diagnosing cancer with another radionuclide for therapy. Although some single radioisotopes decay with emissions suitable for theranostics, it is more common for pairs of radioisotopes to be used (Figure G.1).

A classic example of a theranostic agent in nuclear medicine combines the gamma emission of iodine-123 and beta emission of iodine-131 for diagnosis and therapy of thyroid disorders. Thanks to the availability of radioisotope matched pairs conducive to diagnosis and therapy (for example diagnostic gallium-68 and therapeutic lutetium-177), theranostic approaches have become more common in the past decade. As they show similar chemical properties, lutetium and gallium radiopharmaceuticals can have the same or similar pharmaceutical design (chelate plus a linker to different targeting vectors, such as a variety of peptides, antibodies or small organic molecules). A radiopharmaceutical with a tumour-specific vector radiolabelled with positron emission tomography (PET) diagnostic gallium-68 enables the diagnosis and in-vivo characterization of tumours, thus permitting PET screening, pre-therapeutic proof of target expression, staging and the selection of patients for radionuclide therapy. Patient treatment with a therapeutic lutetium-177 radiopharmaceutical labelled with the same vector offers selective personalized management of a patient's cancer through molecularly targeted radiopharmaceutical therapy.

Currently, gallium-68 and lutetium-177 peptides and enzyme inhibitors are successfully used as vectors for neuroendocrine tumours and prostate cancer. However, there is still a need to find a better diagnostic match for lutetium-177, i.e. a diagnostic radionuclide with more similar chemical properties than gallium-68, as well as a need for pairs of novel alpha, beta or auger emitters and suitably matched diagnostic agents.

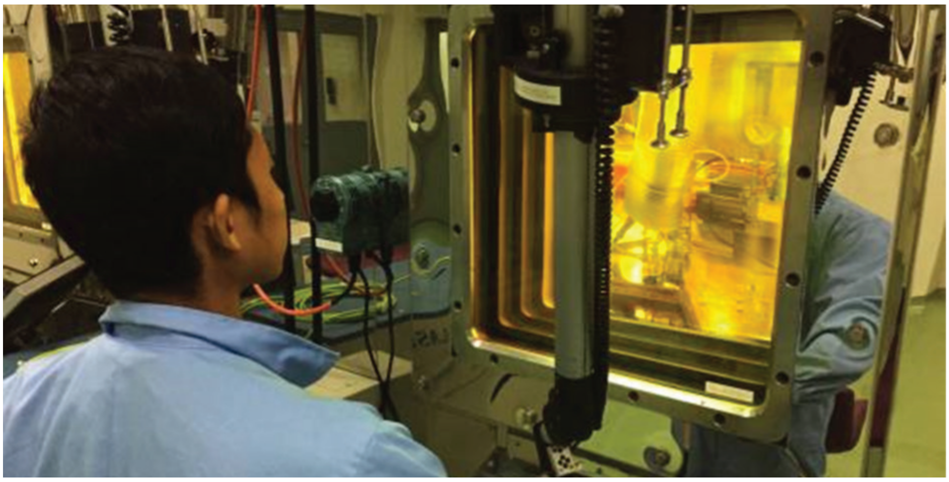


FIG. G.1. Production of theranostic radiopharmaceuticals is ongoing in at least 80 Member States worldwide, using various radioisotopes and carrier molecules. (Photo: IAEA)

Trends

To fully harness the potential of theranostic pairs in nuclear medicine and improve patient outcomes, more research and development on radiopharmaceuticals and radioisotopes are required. The goal is to develop better matched pairs of radionuclides, optimize more stable chelator moieties and broaden the number of specific targeting vectors through biological and biochemical design.

Production of lutetium-177 radiopharmaceuticals is possible in both ‘carrier added’ and ’carrier free’ forms, both currently produced at research reactors. Since 2022, carrier free lutetium-177 can also be produced in nuclear power reactors, with technology developed by Framatome and implemented for the first time in Canada at Bruce NPP. Owing to its medium half-life, its beta particle emissions for therapy and its gamma ray emissions for diagnostic imaging, lutetium-177 is already playing a role in nuclear medicine applications, and has enabled many researchers and scientists to develop new theranostic radiopharmaceuticals. With the recent development of targeting molecules, such as peptides, immune fragments and small molecules, new activities and plans related to the development of agents are under way worldwide.

Theranostic radiopharmaceuticals have already found their way into clinics for cancer therapy. However, recent advances in molecular imaging, such as PET–computed tomography and PET–magnetic resonance imaging, as well as targeted therapy (using alpha and beta emitters), require additional, emerging radioisotopes to be available to clinicians. New radioisotope pairs for theranostic applications, such as terbium radioisotopes with a wide range of diagnostic single photon emission computed tomography and therapeutic (beta and alpha therapy) applications, are under investigation. (Figure G.2)

Thanks to technology developments in radionuclide production, the list of promising radionuclides for radiopharmaceutical applications is growing. Yet, effective delivery of a selected radionuclide to a molecular target within a cell continues to be a challenge in radiopharmaceutical development. Optimized formulation, detailed characterization and preclinical evaluations are required to develop and implement novel and more efficient delivery systems of theranostic products with improved pharmacokinetics and minimal side effects.

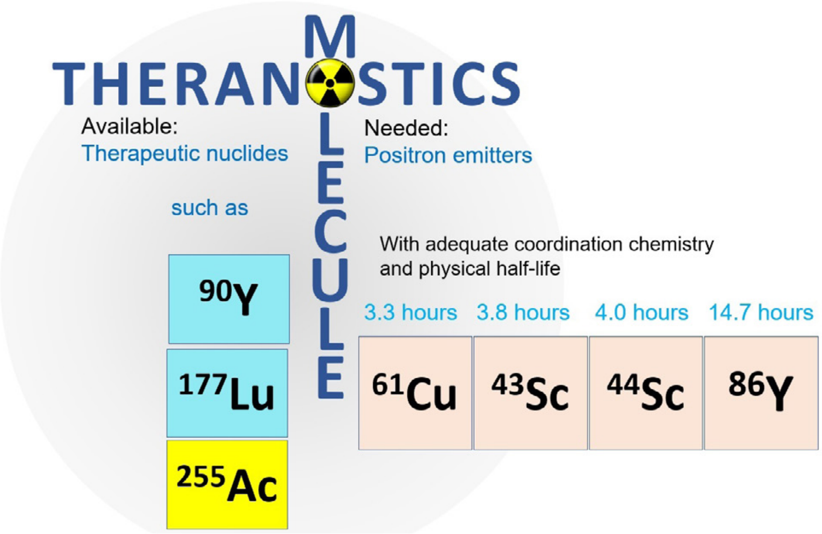


FIG. G.2. Diagram showing the theranostic radioisotopes needed to improve the development of radiopharmaceuticals. (Graphic: IAEA, based on the work of F. Rösch, Johannes Gutenberg University Mainz, Germany)

H.

Human Health

H.
Human Health

H.1.
Artificial Intelligence for Contouring and Radiotherapy Planning

Status

Radiotherapy is an essential pillar of cancer treatment, with about half of all cancer patients needing radiotherapy at some point. Radiation oncology has evolved rapidly in recent decades, with innovations in radiotherapy equipment, three dimensional imaging and information technology, as well as increased knowledge in cancer biology. New delivery technologies and associated imaging modalities using artificial intelligence (AI) have enabled highly optimized precision radiation therapy and contributed to improvements in tumour control and cancer patient care. The use of such tools is expected to lead to reduced inter-observer variation and time savings for clinical staff.

The radiotherapy treatment workflow is a complex process consisting of several time-consuming steps, delivered by different staff groups, that have an impact on treatment quality and hence patient outcomes. There is a global shortage of health care workers, including radiation oncologists, medical physicists and radiotherapy technicians (RTTs). The Agency recommends 1 radiation oncologist per 250 cancer cases[9], which is not realistically achievable for the majority of Member states in the coming decades. AI may offer a solution to the growing need for human resources.

Delivery of radiotherapy requires not only accurate targeting of the tumour, but also the protection of normal tissues and structures to minimize damage and side effects. A critical step in the process of preparing for radiotherapy is contouring, during which organs, normal tissues and the tumour are delineated. These contours generally follow consensus guidelines and atlases (Figure H.1).

Several tools are available or being developed to increase the efficiency of the time-consuming contouring process, such as auto-contouring using atlas-based contours to decrease contour variability. An algorithm selects

FIG. H.1 The Agency trains health professionals in radiotherapy and nuclear medicine services, including through innovative and cost-effective methods. (Photo: IAEA)

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[9] *Setting Up a Radiotherapy Programme: Clinical, Medical Physics, Radiation Protection and Safety Aspects* (IAEA, 2008).

the image most similar to the patient, and deformable image registration is then used to transfer the contours from the atlas to the patient's contours. More recently, large anonymized clinical datasets with high-quality patient contouring data have been used to develop AI-based deep learning algorithms.

Trends

AI can be used as a tool to increase quality, standardization and time saving of the radiotherapy treatment workflow steps. This has the potential to lead to safer and more accurate radiation administration. AI is expanding rapidly into clinical care and is predicted to change the paradigm of radiotherapy planning from a complex process involving many groups of specialists to an automated process. It is essential that health care providers are provided with the training necessary to implement and monitor the related systems safely. It is also essential for the general public to understand the advantages and risks associated.

The selection and contouring of cancer target volumes and organs at risk (OAR) are a key step in modern radiotherapy. Concepts and terms for the definition of gross tumor volume (GTV), clinical target volume (CTV) and OARs have been continuously evolving. The contouring standard remains manual, while auto-contouring workflows can be based on an atlas and deep learning methodology. Atlas-based auto-contouring is based on a 'library' of prepared, contoured computed tomography (CT) cases. Deep learning is a machine learning technique that uses deep neural networks to create a model that can learn and improve with experience and time. Commercially available atlas-based and deep learning auto-contouring packages are available.

While the performance of deep learning-based auto-segmentation in studies is very promising, the actual clinical benefit is largely unstudied. It is possible that contours still require manual human adjustments or checking, and there is a continuous need to educate and put delineation guidelines into practice despite clinical implementation of auto-segmentation. The limitation of using AI for segmentation is that, in some situations, decisions need to be based on more than just imaging information.

A solution to this challenge is hybrid intelligence (HI) combining the strengths of both natural and artificial intelligence for organ segmentation in CT images using five distinct modules[10]. This approach leads to results similar to those achieved by human experts in contouring — but with significant time efficiencies (Figure H.2).

A recent Agency overview of the status, challenges and opportunities related to nuclear technology and AI highlights the need to define the roles and responsibilities of radiotherapy professionals and to provide a clear framework for the selection, commissioning, implementation, data sharing and ongoing quality assurance of AI-based technologies[11].

The Agency will support the development of a framework to guide Member States in the implementation of AI for contouring. As part of this support, a coordinated research project was launched in 2022 to investigate the effectiveness of e-learning interventions for AI-assisted contouring skills in radiotherapy, especially for head and neck cancer. While there are still concerns about the possible disappearance of knowledge among physicians, medical physicists or

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[10] Udupa J. K., Liu T., Jin C., et al. Combining natural and artificial intelligence for robust automatic anatomy segmentation: Application in neck and thorax auto-contouring, Medical Physics (2022).

[11] *Artificial Intelligence for Accelerating Nuclear Applications, Science and Technology* (IAEA, Vienna, 2022).

RTTs, AI appears to be bringing improved quality with greater time efficiencies. Given the global shortage of cancer care workers, with appropriate regulation, increased role of AI in contouring would be a welcome development.

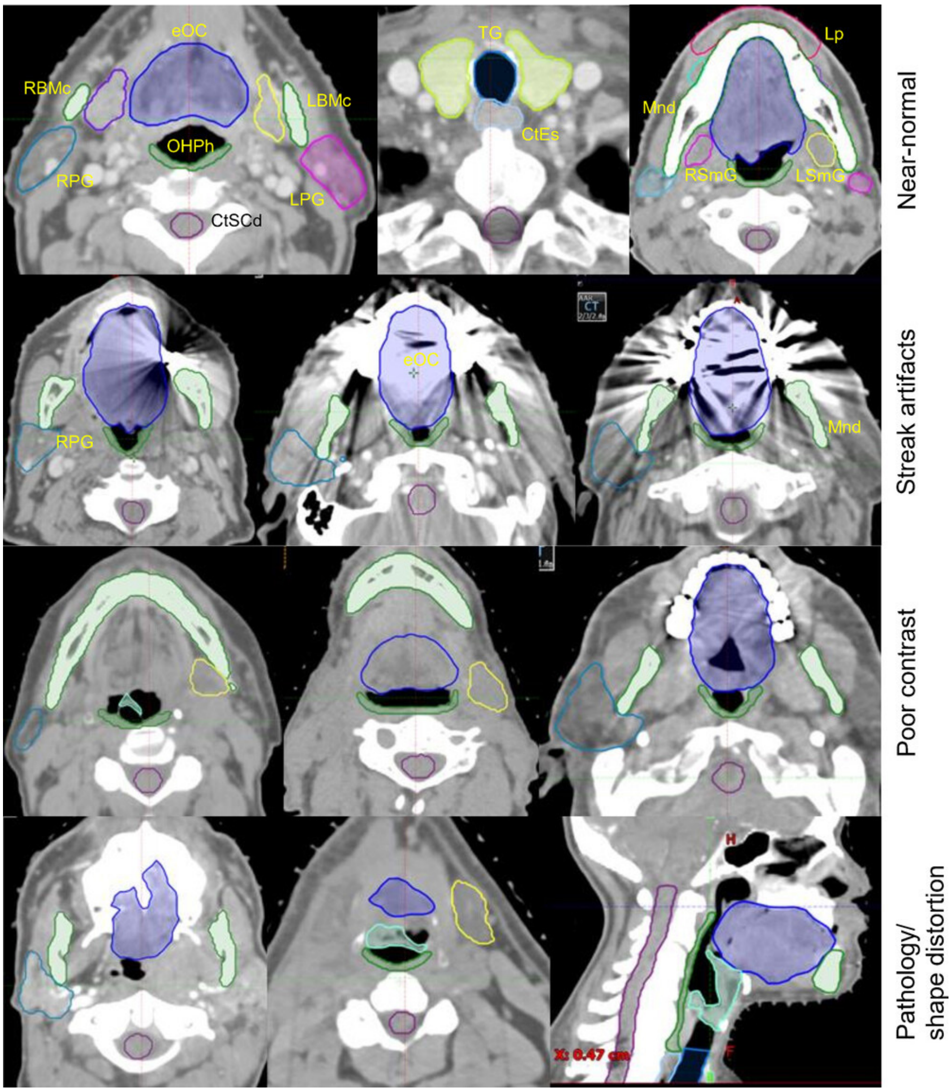

FIG. H.2 Neck CT scans showing image quality deviations, such as streak artifacts, poor contrast and distortion of shapes, which can pose challenges. In such situations, HI can be an effective approach to contouring in radiotherapy. (Photo: Medical Physics, 2022)

I.

Marine Environment

I.
Marine Environment

I.1.
Contaminants of Emerging Concern

Status

It is estimated that over 140 000 synthetic chemicals are manufactured globally, with new anthropogenic chemicals constantly being developed. The frequency of usage and high production volumes of these chemicals, which can harm ecosystems and human health, are projected to triple by 2050. A handful of these chemicals, often referred to as priority substances, are regulated and monitored in the marine environment by Member States. However, only a small fraction of toxic effects observed in the aquatic environment can be attributed to the presence of these known priority substances.[12]

In this context, there is growing concern about contaminants of emerging concern (CECs), substances detected in the environment that do not fall under regulatory surveillance programmes. The fate and biological effects of CECs are poorly understood, despite having known or suspected adverse effects on ecosystems and human health. They include plasticizers, flame retardants, 'non-stick' fluorinated substances (often dubbed 'forever chemicals'), pesticides, pharmaceuticals and personal care products. Industrial and domestic sewage treatment, landfill leachates, surface water run-offs, manure and biosolids applied on agricultural land, and atmospheric deposition are all sources of CECs in the aquatic environment (Figure I.1). Substances that persist for a long time that also bioaccumulate in organisms and have toxic properties are particularly concerning for the health of marine ecosystems.

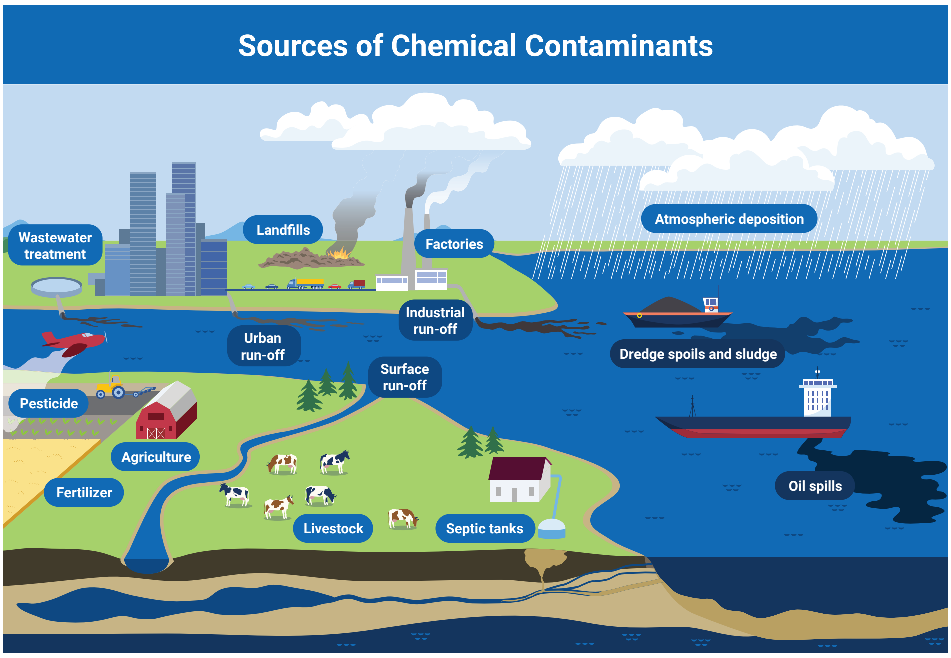

FIG. I.1. An increasing number of new synthetic chemicals are being released into the environment. Innovative water sampling and analytical screening techniques can help scientists identify and quantify the impacts these pollutants have on ecosystems and human health. (Graphic: Rudzhan/stock.adobe.com, modified by the IAEA)

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[12] *See Brack, W., Klamer, H.J.C., Alda, M.L.D. and Barcelo, D., Effect-directed analysis of key toxicants in European river basins: A review, Environmental Science Pollution Research, Vol. 14(1) (2007).*

The IAEA Marine Environment Laboratories in Monaco have been developing analytical methods to target specific compounds within groups of CECs in various marine compartments such as water, sediment and biota. The use of isotopically labelled analogues of these targeted CECs throughout the analytical process combined with mass spectrometric detection techniques allows for the accurate measurement of these contaminants at trace and ultra-trace levels. Such methods, known as 'isotope dilution analysis', are essential to characterize the presence and distribution of known and emerging chemical threats in marine food webs and seafood, especially in regions that are understudied, to inform decision makers with scientific evidence.

However, the warning signals of a 'silent pandemic' are clear and present. The issue of the ever-increasing number of new synthetic chemicals entering the global market is exacerbated by the knowledge gaps regarding their chemical identities. Furthermore, despite the growing body of evidence showing ubiquitous presence of such chemicals in the aquatic environment, there is a deficit in monitoring, assessment and management measures.

Trends

More holistic strategies in monitoring known chemical contaminants and in identifying new, potentially harmful substances in the marine environment are being developed. Combining innovative water sampling tools with advances in mass spectrometric techniques enables more accurate screening of large numbers of known or suspected pollutants and the identification of unknown chemicals.

The advent of passive sampling techniques as reliable, robust and cost-effective tools for water quality monitoring offers a particularly appealing solution to address some of the challenges of chemical pollution specific to the aquatic environment. Passive sampling devices simply consist of either a single material, such as a sheet of silicone rubber, or a material secured behind permeable membranes to accumulate chemical pollutants when deployed in the aquatic environment (Figure I.2).

Passive sampling devices can continuously sample bodies of water over periods ranging from several days to several months. This enables the accumulation of chemical contaminants by factors of several thousand compared to levels typically measured in water, allowing for easier detection where traditional, small volume grab sampling is not sufficiently sensitive.

Stable isotopes in the form of deuterated and carbon-13 labelled reference compounds loaded onto such passive samplers before deployment can enable the accurate quantification of the volumes of water sampled and time-integrated measurements of contaminants. Passive sampling devices also have the advantage of only sampling the freely dissolved fraction of chemicals in the aqueous phase, thereby providing a more accurate representation of bioavailable contaminants that might be taken up by organisms. These devices can even be used to specifically target organic pollutants that are likely to bioaccumulate throughout marine food webs.

When combined with state-of-the art analytical instrumentation using chromatographic separation and high-resolution, high-accuracy mass spectrometry, passive samplers can detect thousands of chemicals present in

FIG. I.2. Passive sampling devices ready for deployment at sea. (Photo: Centre for Environment, Fisheries and Aquaculture Science, United Kingdom)

the marine environment and facilitate the identification of previously unknown compounds. They have the potential to serve as highly effective early warning systems for CECs in the marine environment, and can be deployed in remote or understudied regions and easily transported to analytical laboratories.

These breakthroughs in water sampling and advanced analytical screening techniques can serve as powerful new tools to face some of the challenges presented by complex mixtures of CECs present in the marine environment. Such developments will help fill knowledge gaps with regard to the presence of human-made chemical pollutants, their movement across ecosystems and their subsequent impact on marine ecosystem functions, in order to ensure that their release into the marine environment can be managed at as early a stage as possible.

I.2.

Novel Radiotracers of Ocean Circulation to Improve Understanding and Modelling of the Transport of Pollutants, and Ocean and Climate Change

Status

Over the past several decades, a wide range of radionuclides have been released into the ocean. Their distribution in space and time can be quite complex but is always related to four general processes: the input function/source, radioactive decay, biogeochemistry and oceanic processes. As they are transported throughout the atmosphere and hydrosphere through several physical, chemical and biological pathways, observations of the evolution of their oceanic distribution provide unique information about the nature and magnitudes of the processes at work.

Artificially made radionuclides have been introduced into the marine environment since the 1940s through various activities, including nuclear power generation and the development, production and testing of nuclear weapons. Releases of artificial radionuclides have been meticulously recorded since then, and a significant amount of research has been conducted to address their transport and fate in the marine environment, and to use them as tracers to better understand various marine and oceanic processes. This understanding can provide the basis for assessments of adverse environmental or human health consequences, as well as for rapid assessments of the impact of future radionuclide releases — especially unplanned ones.

Owing to the wide range in the historical and geographical character of the introduction of these substances and to their different environmental behaviours, each tracer illuminates a different portion of the spectrum of oceanic transport processes (Figure I.3). These attributes, in conjunction with an array of geochemical characteristics such as half-life and particle affinity make artificially introduced radionuclides extremely useful tools to better understand ocean patterns and track pollutants.

The use of radiotracers through nuclear techniques, including decay/mass counting and activation by nuclear reactions, is also invaluable for understanding marine and coastal ecosystems. These techniques allow for the monitoring

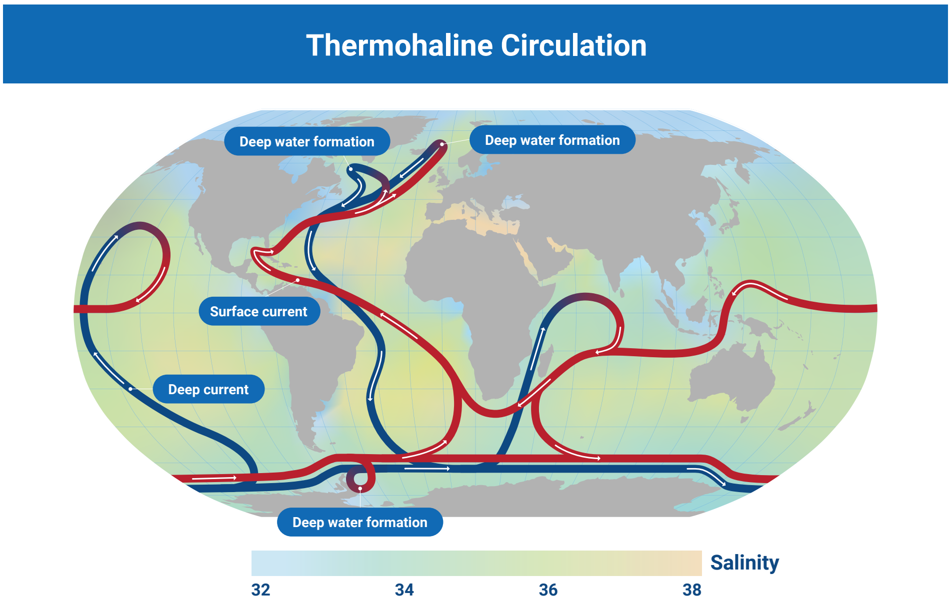

FIG. I.3. Thermohaline circulation, also called the global ocean conveyor belt, is an important mechanism that drives the moving and mixing of water across the ocean. Radiotracers can be used to track the movement of seawater.
(Graphic: NASA Earth Observatory, modified by the IAEA)

of the uptake and biomagnification of radioactive and non-radioactive contaminants such as microplastics and methyl mercury. Such technologies are also used to identify the origin, track pathways and understand the fate of marine microplastic pollution through the projects under the Agency's NUclear TEChnology for Controlling Plastic Pollution (NUTEC Plastics) initiative. They also help identify and quantify biotoxins in seafood, assess impacts of ocean acidification on calcifying organisms and evaluate metabolic processes with increasing temperatures.

As global datasets grow, marine ecosystem modelling is an important analytical approach to integrating knowledge, data and information to better understand ecosystem functioning and contaminant migration and transport. Artificial radionuclides play an important role in helping test the validity of these models by providing ground truth measurement data. An understanding of the processes responsible for transport in the ocean is necessary for predicting human impact on the environment, and for making sound policy decisions on future activities.

Trends

The early days of marine measurements were characterized by sparse and sometimes unreliable data. Sophisticated techniques and new technology enabled the measurement of minute concentrations of material but also brought with them large-volume sample logistics issues and potential severe cross-contamination issues.

The general low level of radionuclides in environmental samples and the small sample sizes available have required the development of efficient techniques. The transition from the counting of radioactive decays to counting atoms using mass spectrometry methods, such as accelerator mass spectrometry (AMS), inductively coupled plasma mass spectrometry, resonance ionization mass spectrometry, secondary ion mass spectrometry and thermal ionization mass spectrometry, is a major paradigm shift in radioanalytical technology.

Recent major advances in AMS regarding detection efficiency and isobar suppression have also opened up possibilities for the analysis of additional long lived radionuclides at ultra-low environmental concentrations (Figure I.4).

The long half-lives of technetium-99, iodine-129, uranium-236, neptunium-237, plutonium-239 and plutonium-240 make them important for oceanographic tracer applications that help study large-scale circulation processes. Studies on water-mass transport processes have put a spotlight on iodine-129 and uranium-236 owing to their soluble nature in seawater and the fact that new advances in measurement techniques enable their detection at extremely low concentrations. In contrast to conventional mass spectrometry techniques, AMS systems determine concentrations from small-volume seawater samples after applying simple and fast chemical procedures with very competitive detection limits (i.e. iodine-129/iodine-127 and uranium-236/uranium-238 atom ratios of 10^{-13} and below).

Ultra-sensitive radioanalytical technologies have always played a key role in marine science. Further developments in new single atom counting technologies will open up opportunities for new and exciting scientific investigations.

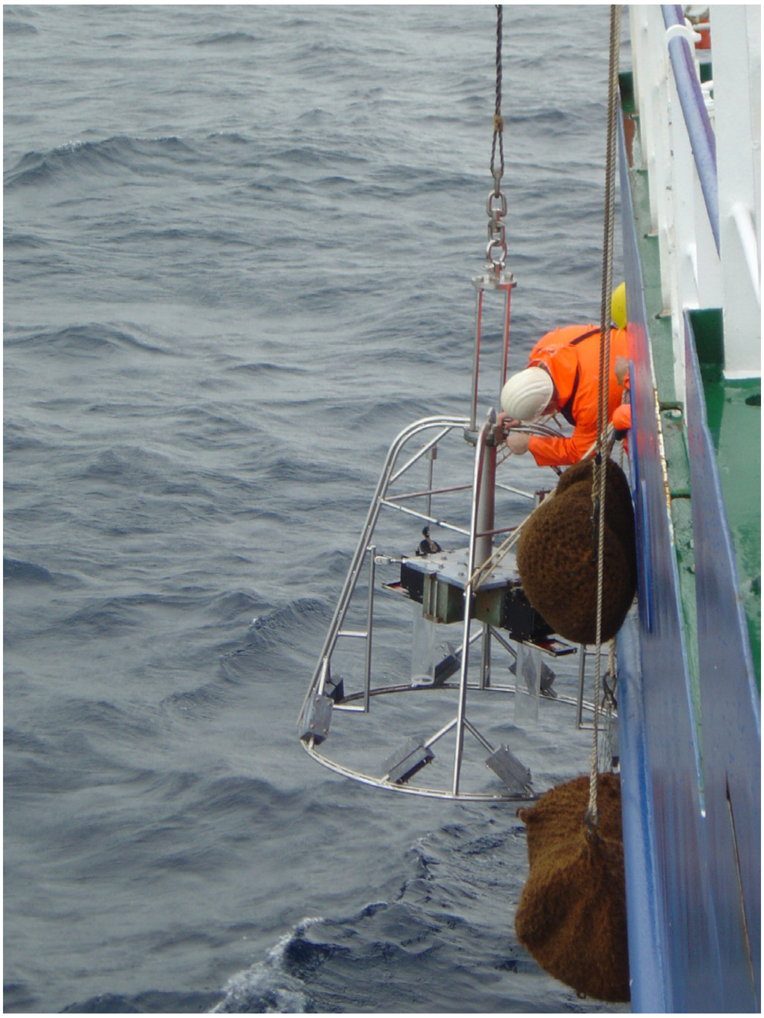

FIG. I.4. A multi-corer being deployed to collect undisturbed sediment samples for analysis of pollutants and signs of climate change. Sediments preserve chronological information, and radiotracers are used to date past events recorded in these natural archives. (Photo: IAEA)

Promising developments in ultra-sensitive laser-based analytical techniques, ultra-trace isotope detection of noble gases, positive ion sources for tandem accelerators, and ion trap technologies are under way. Progress in analytical technologies will further support a transfer from bulk sample analyses to compound-specific isotope analyses with online coupling of analytical instruments. Such advances would make a single atom counting technology available for many radionuclides, which would be a major achievement in ultra-sensitive analysis of marine radionuclides.

Annex

Table A-1. Nuclear power status worldwide – 2022[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2022		Total Operating Experience through 2022	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
Argentina	3	1 641	1	25	7.5	5.4	97	2
Armenia	1	416			2.6	31.0	55	3
Bangladesh			2	2 160				
Belarus	1	1 110	1	1 110	4.4	11.9	2	2
Belgium	6	4 936			41.7	46.4	324	4
Brazil	2	1 884	1	1 340	13.7	2.5	63	3
Bulgaria	2	2 006			15.8	32.5	173	3
Canada	19	13 624			81.7	12.9	903	0
China	54	52 181	20	20 284	395.4	5.0	513	2
Czech Republic	6	3 934			29.3	36.7	188	10
Egypt			2	2 200				
Finland	5	4 394			24.2	35.0	176	2
France	56	61 370	1	1 630	282.1	62.6	2 449	0
Germany	3	4 055			31.9	5.8	834	8
Hungary	4	1 916			15.0	47.0	150	2
India	19	6 290	8	6 028	42	3.1	594	11
Iran, Islamic Republic of	1	915	1	974	6.0	1.7	11	4
Japan	10	9 486	2	2 653	51.9	6.1	2 020	6
Korea, Republic of	25	24 489	3	4 020	167.5	30.4	644	9
Mexico	2	1 552			10.5	4.5	61	11
Netherlands	1	482			3.9	3.3	78	0
Pakistan	6	3 262			22.2	16.2	98	9
Romania	2	1 300			10.2	19.3	41	11
Russian Federation	37	27 727	3	2 700	209.5	19.6	1 447	7
Slovakia	4	1 868	2	880	14.8	59.2	184	7
Slovenia	1	688			5.3	42.8	41	3
South Africa	2	1 854			10.1	4.9	76	3
Spain	7	7 123			56.2	20.3	368	2
Sweden	6	6 937			50.0	29.5	486	0
Switzerland	4	2 973			23.2	36.4	236	11
Türkiye			4	4 456				
Ukraine[e]	15	13 107	2	2 070	NA	NA	563	6
United Arab Emirates	3	4 011	1	1 310	19.3	6.8	4	0
United Kingdom	9	5 883	2	3 260	43.6	14.2	1 658	9
United States of America	92	94 718	2	2 234	772.2	18.2	4 825	9
Worldwide[b,c]	**438[d]**	**393 823[d]**	**58**	**59 334**	**2 486.6**	**NA**	**19 764**	**11**

Note: NA — Not Available.

[a] Source: Agency's Power Reactor Information System (PRIS) (www.iaea.org/pris) as per data provided by Member States by the end of June 2023.

[b] The total figures include the following data from Taiwan, China: 3 units, 2 859 MW(e) in operation and 22.9 TW·h of electricity supplied, accounting for 9.1% of the total electricity mix.

[c] The total operating experience also includes shutdown plants in Italy (80 years, 8 months), Kazakhstan (25 years, 10 months), and Lithuania (43 years, 6 months), and shutdown and operational plants in Taiwan, China (239 years, 8 months).

[d] The total figures include data for units where operation remained suspended: India (4 units; 639 MW(e)) and Japan (23 units, 22 193 MW(e)).

[e] The total electricity production does not include Ukrainian reactor units as operational data were not submitted for the year 2022 by the time of publication.

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	161	51
Neutron activation analysis	116	50
Radioisotope production	82	41
Neutron imaging	69	37
Material/fuel irradiation	68	26
Neutron scattering	44	28
Geochronology	24	21
Transmutation (silicon doping)	23	15
Transmutation (gemstones)	20	12
Neutron therapy, mainly R&D	15	12
Nuclear data provision	16	9
Other[c]	116	34

[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 233 research reactors considered (223 in operation, 10 temporarily shut down, as of December 2022).

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

List of Abbreviations

AEC	alkaline electrolytic cell
AGR	advanced gas cooled reactor
AI	artificial intelligence
ALFRED	Advanced Lead Fast Reactor European Demonstrator
ALPS	Advanced Liquid Processing System
AMR	antimicrobial resistance
AMS	accelerator mass spectrometry
ANSTO	Australian Nuclear Science and Technology Organisation
ATF	advanced technology fuel
ATF-TS	Advanced Technology and Accident Tolerant Fuels
BIS	bid invitation specification
BNCT	boron neutron capture therapy
CECs	contaminants of emerging concern
COP27	2022 Conference of the Parties to the United Nations FrameworkConvention on Climate Change
COVID-19	coronavirus disease 2019
CRP	coordinated research project
CT	computed tomography
CTV	clinical target volume
D10	decimal reduction dose
DEMO	demonstration fusion power plant
DGR	deep geological repository
DOE	Department of Energy
DSRS	disused sealed radioactive source
DTT	Divertor Tokamak Test
EDXRF	energy dispersive X-ray fluorescence
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GC–IMS	gas chromatography–ion mobility spectrometry
GTV	gross tumor volume
GW	Gigawatt
GW(e)	gigawatt (electrical)
HALEU	high assay low enriched uranium
HEU	high enriched uranium
HI	hybrid intelligence
HPR1000	Hualong One
HTR–PM	High Temperature Reactor–Pebble-Bed Module
IFMIF	International Fusion Materials Irradiation Facility
IMSR	Integral Molten Salt Reactor

INIR	Integrated Nuclear Infrastructure Review
ISR	in situ recovery
keV	kiloelectronvolt
KP-FHR	Kairos Power fluoride salt cooled high temperature reactor
KSTAR	Korea Superconducting Tokamak Advanced Research
LEU	low enriched uranium
LFR	lead cooled fast reactor
LIDAR	light detection and ranging
LILW	low and intermediate level waste
LLNL	Lawrence Livermore National Laboratory
LTO	long term operation
LWR	light water reactor
MeV	megaelectronvolt
MHTGR	modular high temperature gas cooled reactor
ML	machine learning
MMR	Micro Modular Reactor
MOX	mixed oxide
MSFR	molten salt fast reactor
MSR	molten salt reactor
MW(e)	megawatt (electrical)
NHSI	Nuclear Harmonization and Standardization Initiative
NIF	National Ignition Facility
NORM	naturally occurring radioactive material
NPP	nuclear power plant
NPPA	Nuclear Power Plants Authority
OAR	organs at risk
PET	positron emission tomography
PEM	polymer electrolyte membrane
PRIS	Power Reactor Information System
PWR	pressurized water reactor
R&D	research and development
RD&D	research, development and demonstration
RTT	radiotherapy technician
SCWR	supercritical water cooled reactor
SDA	standard design approval
SFR	sodium cooled fast reactor
SMART	system-integrated modular advanced reactor
SMRs	small and medium sized or modular reactors
SNF	spent nuclear fuel

STEP	Spherical Tokamak for Energy Production
t HM	tonnes of heavy metal
TRIC	Tritium Intercomparison Exercise
TRISO	fuel tristructural isotropic fuel
TW·h	terawatt hour
UAV	uncrewed aerial vehicle
WAC	waste acceptance criteria
WCR	water cooled reactor
WHO	World Health Organization

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