Nuclear Technology Review 2022

Report by the Director General

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

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Foreword

- 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 2021.

- The *Nuclear Technology Review 2022* covers the following select areas: nuclear power, nuclear fuel cycle, decommissioning, environmental remediation and radioactive waste management, research reactors and particle accelerators, atomic and nuclear data, environment, food and agriculture, human health, radioisotopes and radiation technology, and artificial intelligence for nuclear sciences and applications.

- The draft version was submitted to the March 2022 session of the Board of Governors in document GOV/2022/2. This final version was prepared in the light of the discussion held during the Board of Governors and also of the comments received by Member States.

Foreword by the Director General

Climate change, air pollution, energy security, food security, plastic pollution, cancer and obesity are among the many global challenges the world community faces.

In tackling all of these, we must use all the tools we have.

Nuclear technologies, in combination with others, help Member States make informed decisions on the appropriate course to take — whether in using artificial intelligence for all things nuclear, producing reliable and low carbon energy, helping understand and fight plastic pollution, or save lives through better cancer care and nutrition.

At the 2021 Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26), held in Glasgow, United Kingdom, the Agency contributed to the debate through its unique science and evidence-based approach showing how nuclear technology is vital in both fighting the climate crisis and in effectively coping with its increasingly severe consequences. Reflecting the growing role of nuclear technologies, the Agency will continue to engage in high level dialogue on nuclear energy and nuclear techniques and applications at COP27, to be held in Sharm el-Sheikh, Egypt.

The *Nuclear Technology Review 2022* summarizes the status of some key nuclear technology fields and highlights novel, promising developments in them.

FIG. FW-1. Rafael Mariano Grossi, IAEA Director General, visiting the Admiral Alvaro Alberto Nuclear Power Plant. (Rodovia Rio-Santos - Itaorna, Angra dos Reis, Brazil)

Executive Summary

For the first time since the Fukushima Daiichi nuclear power plant (NPP) accident a decade ago, the Agency has revised up its projections of the potential growth of nuclear power capacity for electricity generation during the coming decades. Overall, nuclear power capacity has gradually increased over the past decade, including some 20.7 GW(e) of capacity increase due to the connection of new units to the grid and capacity uprates to existing reactors.

At the end of 2021, the global operating nuclear power capacity was 389.5 GW(e) provided by 437 operational nuclear power reactors in 32 countries. In the course of the year, over 5.2 GW(e) of new nuclear capacity was connected to the grid from four new pressurized water reactors in China, Pakistan and the United Arab Emirates, one pressurized heavy water reactor in India and one high temperature gas cooled reactor in China. During the same period, 8.7 GW(e) of nuclear capacity was permanently retired.

A total of 26 Member States were at various stages of preparing their national infrastructure for a new nuclear power programme, with 10 to 12 newcomers expected to introduce nuclear power by 2035, increasing the number of operating countries by a third. One significant technological development attracting the attention of energy planners and policy makers is the expected availability and deployment of several first-of-a-kind small and medium sized or modular reactors (SMRs) by 2030. As a result, several newcomer countries have included SMRs in their technology considerations even if advanced large water cooled reactors are still expected to make up the bulk of new capacity additions over the next three decades. National nuclear power infrastructure is needed to maintain the same constant strict attention to nuclear safety, nuclear security and safeguards requirements for large advanced reactors and SMRs.

Nuclear power plants around the world continued reliable operations during the COVID-19 pandemic through the implementation of innovative operational approaches and specific measures to protect workers. The nuclear power fleet again demonstrated its ability of provide resilient, reliable and adaptable operations during such challenging times.

Long term operation remained essential, not only for the low carbon energy transition and for meeting net zero carbon objectives, but also to allow time to build up new low carbon generation capacity, including new nuclear power plants.

Many Member States made tangible progress in SMR technology development for near term deployment. In addition to the Akademik Lomonosov floating nuclear power plant in the Russian Federation that has been in commercial operation since May 2020, China started the construction of a 125 MW(e) ACP reactor. Currently, there are more than 70 small modular reactor designs under development for electrical and non-electrical applications. Development activities for a subset of SMRs known as microreactors envisioned as the optimum solution for providing cogeneration of heat and electricity in remote regions or small islands, and/or to replace diesel generators, also intensified in several countries. To assist Member States in achieving a common understanding of their needs and specificities on small modular reactor technology, the Agency initiated a new framework for the development of generic user requirements and criteria for SMR design and technology.

The use of nuclear energy beyond electricity production is enjoying unprecedented momentum worldwide. During 2021, a total of 61 operating nuclear reactors were used for non-electric applications (desalination, district heating and process heating) to generate about 2167 GW·h of electrical equivalent heat to support nuclear cogeneration, including 5 reactors supporting desalination.

The ITER project maintained steady progress in machine and plant assembly despite unprecedented pressure due to the pandemic and the difficulties encountered in manufacturing some of ITER's first-of-a-kind components. Substantial progress was made in the ITER machine assembly and integration. A number of initiatives towards the establishment of a specific regulatory framework for fusion, one of the key elements in the development of fusion as a commercially viable source of energy at the national level, have started.

The sustained low price of uranium forced several primary uranium producers to reduce production rates. This has prompted several investors, funds, traders and primary uranium producers to purchase triuranium octaoxide (U3O8) on the market in response to the forecasted shift in the supply-demand for U3O8. As a result of reduced inventories and the accelerated trading of U3O8 in 2021, the spot price had significantly increased by the end of the year since the first quarter of 2021. Recent increases in the uranium market price have incentivized some investments with some renewed exploration and development activity in 2021 as well as restarting of some primary production.

Many of the issues which have led to the shutdown of nuclear facilities over the past decade — political and economic factors, maintenance and/or refurbishment costs, and electricity market conditions — are expected to continue to apply in the future; indeed, the rate of shutdowns may accelerate due to the age profile of the current fleets, partly compensated by lifetime extensions. A large majority of the approximately 300 nuclear power reactors which are currently 30 years old or more may be retired from service over the next three decades. A similar development is anticipated in the case of research reactors as this fleet has a broadly similar age profile. The current trends appear to be favouring a more immediate dismantling approach as opposed to deferred dismantling which was historically the preferred strategy.

Some Member States made significant steps in 2021 towards the final stages of disposal at their low level waste facilities. With regard to deep geological repository (DGR) programmes for high level waste, the Finnish waste management organization Posiva started excavation of the first disposal tunnels in 2021 at the Onkalo DGR site. International collaboration continues to expand in the field of radioactive waste management, especially for deep geological disposal programmes. Significant progress for the management of disused sealed radioactive sources, specifically in terms of retrieval and conditioning, was also made in 2021.

Global interest in research reactors continued to grow. In addition to 235 operational research reactors, eleven were under construction in 2021. Many countries take advantage of opportunities to access research reactors through international and regional collaboration initiatives. Two Internet Reactor Laboratories, in the Czech Republic and the Republic of Korea, started transmissions of experiments to students in other countries.

With the advent of powerful computing capabilities and data analysis tools, the nuclear industry is embracing artificial intelligence, machine learning and deep learning techniques for a wide range of activities that could transform the way nuclear systems are being designed, licensed and operated. Artificial intelligence has the potential to enhance the integration of computations and experimental data collected from small scale experiments or from sensors during operation. The rapid adoption of artificial intelligence/machine learning in various domains is a clear trend that will also heavily influence nuclear physics and nuclear data library development.

Artificial intelligence also has enormous potential to accelerate technological development in many nuclear fields from human health to fusion and nuclear science. By enabling experts to quickly analyse huge amounts of water-related isotopic data stored in global networks, artificial intelligence already helps scientists understand the impact of climate change and population growth on water resources. It can contribute to combating cancer and better preparations for future zoonotic disease outbreaks. Enhanced use of artificial intelligence in nuclear sciences and applications requires strong international partnerships and cross-cutting cooperation for the development of guidance in regulation, ethical issues, education and training as well as for sharing experiences, knowledge and good practices.

Accelerator mass spectrometry (AMS) has proven to be an ultra-sensitive technique with great potential for analytical applications related to problems of modern society. AMS is presently used in archaeology, biomedicine applications, climate change studies, hydrology, oceanography and many other fields of increasing societal and economic concern. Recent technological developments have also expanded the field of its applications, allowing the study of a wide range of cultural and natural heritage objects as well as the detection of forgeries and the illicit trade of products.

Innovative radiation technologies for recycling and isotopic tracing techniques for monitoring in the ocean offer solutions to tackle plastic pollution, one of the most pressing global environmental challenges and a direct threat to sustainable development. The NUclear TEChnology for Controlling Plastic Pollution (NUTEC Plastics) initiative, launched in 2021, builds on the Agency's efforts to deal with plastic pollution through recycling using radiation technology and marine monitoring using isotopic tracing techniques.

The innovative application of gamma and electron beams can enable effective sorting of plastic wastes to feed into recycling streams. Nuclear and isotopic techniques, together with ocean circulation and dispersion modelling, contribute to tracing the sources of plastics and their fate in the ocean. They help scientists to reconstruct the historical trends of marine plastic pollution and better understand the post-sedimentation ageing of microplastics.

Misuse and overuse of antimicrobial substances, such as antibiotics, antivirals, antifungals and antiparasitics, which are used to prevent and treat infections in humans, animals and plants, is a global public health threat, currently leading to 700 000 deaths every year. Compound specific stable isotope analysis and probing technologies are powerful tools for the assessment of antimicrobial substances. The integration of such isotopic and advanced molecular techniques is expected to help better understand the fate and dynamics of antibiotics in applied manure and its implications on antibiotic resistance in the environment.

There is increasing interest in understanding the effect of the space environment on producing mutations in plant genomes and in modifying plant physiology, thus improving the ability of plants to withstand adverse growth conditions on Earth such as those induced by climate change. Rapid advances in the field are foreseen with continuing interest to explore plant biology in space, both for feeding astronauts and for using valuable mutations from space exposure to breed resilient crop varieties.

In cancer management, isotope-based theranostics refers to the combination of diagnosis and therapy, enabling medical professionals to focus on the specific needs of each patient. Compared to conventional radiation treatments, the theranostic approach allows for greater specificity by targeting the tumour with radioactive bullets while sparing the surrounding healthy tissues, increasing both the effectiveness as well as the safety of the treatment. Currently the most prominent applications are focused on neuroendocrine tumours, lymphoma, prostate, breast, lung and thyroid cancers. There is a growing need for broader international cooperation and standardization in training medical and scientific experts and establishing specialized medical infrastructure.

Obesity related illness has reached epidemic proportions globally, with at least 2.8 million people dying each year as a result of being overweight or obese. Obesity related illness is estimated to cost $1.2 trillion yearly by 2025. Data on energy expenditure provided by the stable isotope technique of doubly labelled water (DLW) are crucial and will provide policy makers with the evidence to devise more effective nutrition and health policies to combat a growing obesity epidemic worldwide. However, more data are needed from low and middle income countries to strengthen global representation in studies and enable policy makers to have the evidence available to prioritize essential nutrition actions and tackle the obesity epidemic.

Used both for diagnosis and therapy in cancer and other chronic diseases, radioisotopes and radiopharmaceuticals save lives. Ensuring a constant supply of key radioisotopes is essential. Two new production routes, using linear accelerators and nuclear power plants, open horizons for strengthening and empowering the global supply chain of the world's most used medical radioisotope, molybdenum-99. Production of molybdenum-99 using high energy electron beams has already been commercialized.

Radioisotope production in nuclear reactors is based on neutron capture reactions in a target material. Typically research reactors are used to produce radioisotopes for therapeutic applications in nuclear medicine. Irradiation of targets at nuclear power plants is the usual route for producing radioisotopes such as cobalt-60, used in industry and brachytherapy. In 2021, a commercial CANDU-type reactor was authorized by the regulator to produce molybdenum-99. Producing other important short lived medical radioisotopes, including lutetium-177 and holmium-166 is being explored. This may provide new horizons for designers to consider power reactors with radioisotope production capacity.

A.
Nuclear Power

A.
Nuclear Power

A.1.
Nuclear Power Projections

Status

For the first time since the Fukushima Daiichi accident a decade ago, the Agency has revised up its projections of the potential growth of nuclear power capacity for electricity generation during the coming decades. The change in the Agency's annual outlook for this low carbon energy source does not yet mark a new trend, but it comes as the world aims to move away from fossil fuels to fight climate change. Many countries are considering the introduction of nuclear power to boost reliable and clean energy production. Positive and high level discussions on the use of nuclear power took place at the 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) in Glasgow, United Kingdom, in November 2021 — a first in many years of COP (Figure A.1).

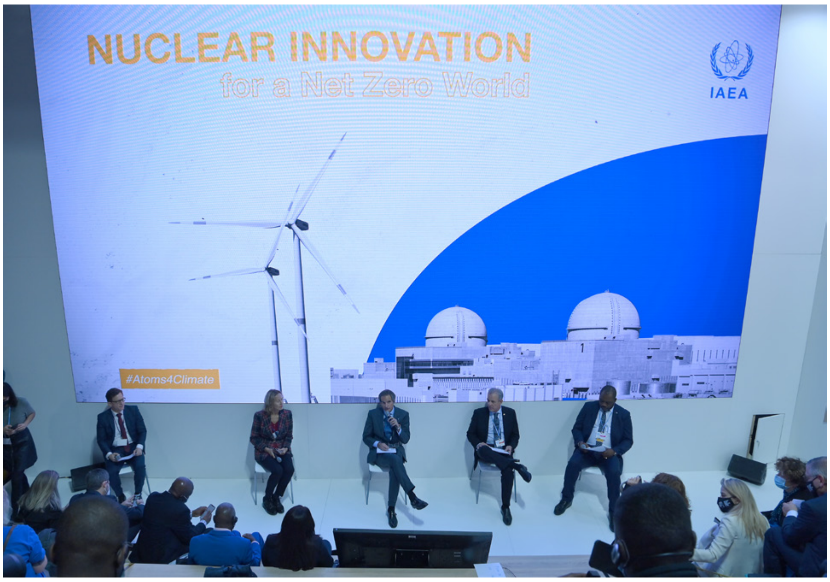


FIG. A-1. High level conversation on nuclear at COP26 between Director General Grossi, Minister Albuquerque of Brazil, Minister Prempeh of Ghana and UNECE Executive Secretary Algayerova

Compared to the global installed capacity in 2020 — 392 GW(e), corresponding to a share of 10.2% of electricity generation — the low case estimate sees global nuclear power capacity remain essentially the same at 394 GW(e) in 2050, with a drop in the share of global electricity generation to 6.3%. The high case estimate, on the other hand, projects more than a doubling of installed capacity to 792 GW, corresponding to an increased share of electricity generation of 12.3% (Figure A.2).

To achieve the high case projection, both extensive long term operation (LTO) of the existing nuclear power reactor fleet (typically beyond 40 years of operation) and a significant effort to build 550 GW(e) of new capacity over three decades will be required. To achieve this, connection rates of new reactors need to at least double in the coming decades, and accelerated demonstration and deployment of innovative reactor technologies will also be required.

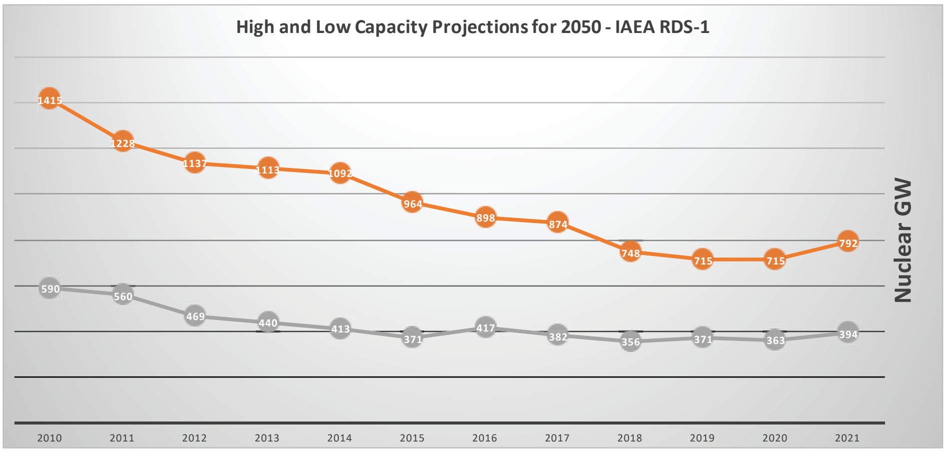


FIG. A-2. Evolution of high and low nuclear power capacity projections for 2050 based on data presented in RDS-1 editions from 2010-2021.

Trends

There is considerable and growing interest in innovative reactor technologies, including in small and medium sized or modular reactors (SMRs). However, advanced large water cooled reactors 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. The nuclear sector will continue to address a number of challenges including cost reductions and enhanced standardization to improve competitiveness.

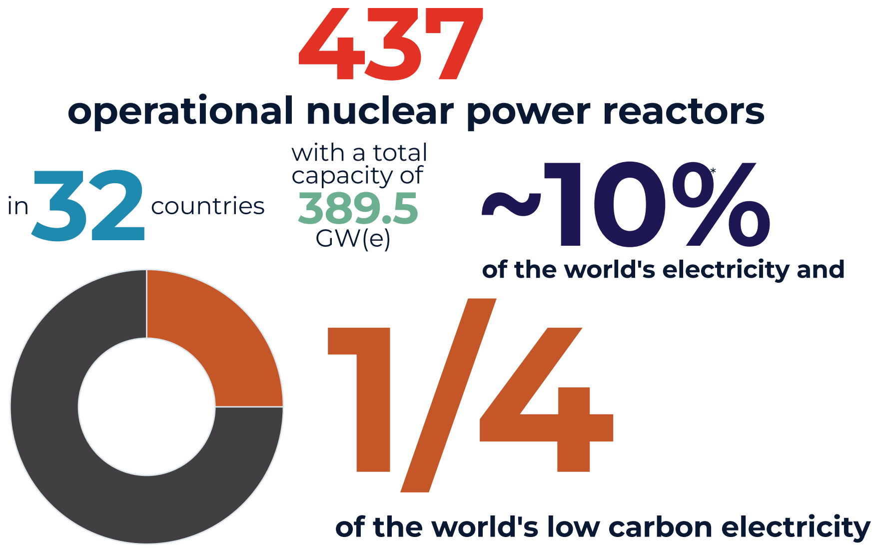
Strong policy support, recognizing the contribution of nuclear power to resilient and reliable low carbon power systems, will be needed, including access to financing on a level playing field with other low carbon energy sources. Promoting opportunities for nuclear energy to contribute to the decarbonization of other energy sectors, including through the production of clean hydrogen, could also make nuclear power a more attractive option for investors..

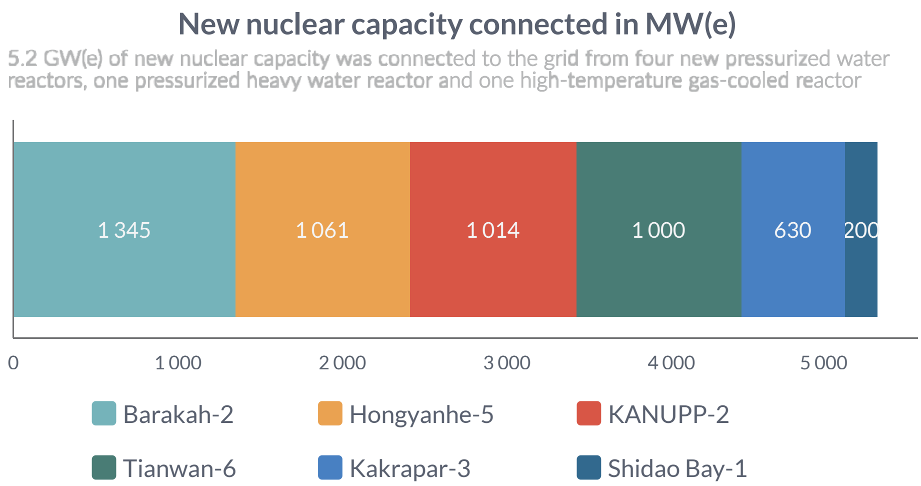
A.2. Operating Power Plants

Status

At the end of 2021, the world's total nuclear power capacity was 389.5 GW(e), provided by 437 operational nuclear power reactors in 32 countries (see Table A-1). Countries continued demonstrating adaptability to the COVID-19 pandemic by taking effective measures to ensure safe and reliable operation while minimising risks to staff, reflecting strong organizational culture. During 2021, the Agency continued to share information on measures taken to mitigate the effects of the pandemic and its impact on the operation of NPPs through the COVID-19 Nuclear Power Plant Operating Experience Network. None of the 32 countries with operating nuclear power plants reported that the pandemic had induced an operational event impacting safe and reliable NPP operation.

As a clean, reliable, sustainable and modern energy source, nuclear power makes a significant contribution to reducing greenhouse gas emissions worldwide, while fulfilling the world's increasing energy demands and supporting sustainable development and post-COVID-19 pandemic recovery. Over 5.2 GW(e) of new nuclear capacity was connected to the grid from six new reactors. These include four new pressurized water reactors (PWRs) (Tianwan-6 (1000 MW(e)) and





Hongyanhe-5 (1061 MW(e)) in China, KANUPP-2 (1017 MW(e)) in Pakistan, and Barakah-2 (1310 MW(e)) in the United Arab Emirates), one pressurized heavy water reactor (PHWR) (Kakrapar-3 (630 MW(e))) in India, as well as one high temperature gas cooled reactor (HTGR) (Shidao Bay-1 (200 MW(e))) in China (Figure A.3).

LTO and ageing management programmes were under way for an increasing number of nuclear power reactors globally, especially in North America and Europe. The US Nuclear Regulatory Commission (NRC) approved an application for 20-year extensions to the operating licences submitted by Dominion Energy for the Surry-1 and Surry-2 reactors in southeastern Virginia. This will extend the lifetime of these two power reactors to 80 years, allowing them to operate until 2052 and 2053, respectively. Also, the French Nuclear Safety Authority (ASN) announced that it had completed its review of the plan by Électricité de France (EDF) to extend the lifespan of 32 reactors in the 900 MW(e) fleet for another ten years. The ASN concluded that the measures planned by EDF combined with those prescribed by the ASN opened the prospect of continued operation of these reactors for a further ten years following their fourth periodic safety review. The updated design studies and equipment replacements required for extended operations of the Tricastin-1 and Bugey-2 reactors have already completed, allowing the reactors to operate until 2031.

FIG. A-3. In December 2021, Director General Rafael Mariano Grossi visited the Barakah Nuclear Power Plant in the United Arab Emirates and met young nuclear professionals.

During 2021, 8.7 GW(e) of nuclear capacity (ten reactors) was permanently retired. Half of that lost capacity resulted from the shutdown of three reactors in Germany: Brokdorf (PWR, 1410 MW(e)), Grohnde (PWR, 1360 MW(e)) and Gundremmingen-C (BWR, 1288 MW(e)). Three gas cooled reactors — Dungeness B-1 (545 MW(e)), Dungeness B-2 (545 MW(e)) and Hunterston B-1 (490 MW(e)) — were retired in the United Kingdom. The other three reactors that were shut down were KANUPP-1 (PHWR, 90 MW(e)) in Pakistan, Kursk-1 (light water cooled, graphite moderated reactor, 925 MW(e)) in the Russian Federation, and Indian Point-3 (PWR, 1030 MW(e)) in the United States of America. Kuosheng-1 (BWR, 985 MW(e)) in Taiwan, China, was also shut down.

Trends

Overall, nuclear power capacity has gradually increased over the past decade, including some 20.7 GW(e) of capacity increase as a result of the connection of new units to the grid and capacity uprates to existing reactors (Figure A.4).

FIG. A-4. Rafael Mariano Grossi, IAEA Director General, visiting the Admiral Alvaro Alberto Nuclear Power Plant in Brazil and witnessing the construction of the Angra III reactor.

LTO is essential, not only for the transition to low carbon electricity systems and for meeting net zero carbon objectives, but also to allow time to build up new low carbon generation capacity, including new nuclear power plants. Moreover, existing nuclear power plants are the cheapest source of safe and secure low carbon electricity. However, some reactors were shut down in the past decade, and others are likely to be closed for economic reasons in the near term, despite operators receiving licences for extended operation. In addition, the existing supply chains were facing challenges that could impact ongoing operations, projects and outage planning. Nevertheless, new supply chains are emerging in newcomer countries, which may bring new actors to the field.

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, Niger, Philippines, Senegal, Sri Lanka, Sudan, Thailand, Tunisia, Uganda, 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 (Bangladesh, Egypt, Ghana, Kenya, Jordan, Nigeria, Poland, Saudi Arabia, Türkiye, Uzbekistan).

In Bangladesh, construction of the first NPP is ongoing with planned commercial operation for the two units starting in 2024 and 2025 respectively. The construction of four units at Akkuyu NPP in Türkiye continued in 2021. Commissioning of the four units is anticipated for 2023–2026. In Egypt, the Nuclear Power Plants Authority (NPPA) applied for a construction licence for El Dabaa units 1 and 2 in July 2021. Site preparation for construction continues. Both key organizations (NPPA and the Egyptian Nuclear and Radiological Regulatory Authority) are undergoing restructuring based on the needs of the programme. In Poland, the PGE EJ 1 company was fully acquired by the State Treasury in March 2021 and renamed PEJ. PEJ will act as the investor for planned PWRs with a total of 6000–9000 MW(e) installed nuclear power capacity by 2042. The construction of the first two NPPs is planned to start in 2026 and 2032 with commissioning of the first unit in 2033. In Argentina, the construction of CAREM, located on the site bordering the Atucha 1 plant, is in an advanced stage, with a view to producing 32 MW(e) as a demonstration of the prototype.

In Saudi Arabia, the bid invitation specification (BIS) for the procurement of the first two NPP units of 1000–1600 MW(e) is currently being developed. Jordan has decided to pursue two parallel paths for the development of a nuclear power programme with a large NPP (1000 MW(e) on a build–own–operate–transfer basis) and SMRs as first priority. The BIS documents for the SMR project have been drafted and are expected to be finalized and announced by the beginning of 2022. Ghana continued to work on developing its national infrastructure for a nuclear power programme including further development of the capacities of the key organizations. A request for interest of potential vendors was issued by the Ministry of Energy for the development of around 1000 MW(e) capacity. 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 both a research reactor and a large NPP as well as explore SMRs. Nigeria has resumed activities on its nuclear power programme after delays resulting from organizational changes in the key organizations and the COVID-19 pandemic, including updating its pre-feasibility and feasibility studies to reassess the economic viability of the NPP project. 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, Türkiye) have included nuclear in their Nationally Determined Contributions (NDCs) submitted to the UNFCCC under the Paris Agreement.

In 2021, three Agency Integrated Nuclear Infrastructure Review (INIR) missions were hosted by Kenya (Phase 1 Follow-Up), Uganda (Phase 1) and Uzbekistan (Phase 2). The planned mission to Sri Lanka (Phase 1) was postponed due to COVID-19 (Figure A.5). The Agency also received requests for INIR Phase 1 mission from Zambia and INIR Phase 3 mission from Bangladesh, under preparation to be conducted in 2022 and 2023 respectively.

Furthermore, 15 Member States have active Integrated Work Plans (IWPs). Due to the implications of COVID-19, the IWPs were reviewed in full or as mid-term reviews through virtual meetings with the core teams.

In Uzbekistan, construction of NPPs with a total of 2.400 GW(e) of installed capacity is planned to begin by the end of 2022. Ghana plans to start construction of its first NPP in 2023 and commissioning in 2029. Kenya established a new organization, the Nuclear Power and Energy Agency, and a strategic environmental assessment report was released for public consultations, with deployment of the

FIG. A-5. IAEA reviews Uganda's nuclear power infrastructure development.

NPP foreseen by 2035. In July 2020, the Philippines issued an executive order creating the Nuclear Energy Programme Inter-Agency Committee to study the feasibility of introducing nuclear power. Sri Lanka officially requested an INIR mission.

Integrated Nuclear Infrastructure Review Missions

2021

3 missions hosted
Kenya
Uganda
Uzbekistan

1 mission postponed
Sri Lanka

2022

1 Phase 1 mission under preparation
Zambia

2023

1 Phase 3 mission under preparation
Bangladesh

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.

One significant technological development attracting the attention of energy planners and policy makers 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 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.

It should be emphasized that the national nuclear power infrastructure requires the same constant strict attention to nuclear safety, nuclear security and safeguards requirements, whether the programme is based on large NPPs or SMRs.

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.

A.4. Nuclear Power Technology Development

Status

Evolutionary nuclear power reactors, i.e. designs, which involve only moderate modifications or improvements over current NPP fleet, are already a very well consolidated reality in many parts of the world. Advanced water-cooled reactors are in operation in Belarus, China, Japan, Russian Federation, UAE. In other countries like Argentina, France, Finland, UK and USA, advanced water cooled reactors of different power capacity are in advanced stage of construction and in some cases under commissioning. Two industrial size sodium-cooled fast reactors are in operation in the Russian Federation where also the first-of-a kind lead cooled fast reactor has started construction. Fast reactors are also in operation or under construction in China and India. The first modular high temperature gas cooled reactor using pebble bed technology has been connected to the grid in China in December 2021.

In parallel there is a growing interest of Member States for the quick development and early deployment of innovative reactors, i.e. advanced designs which incorporate conceptual changes in the design approaches or system configuration in comparison with existing practice. There are innovative concepts under development in all principal reactor lines, i.e. water cooled reactors, high and very high temperature gas cooled reactors, sodium, lead and gas-cooled reactors with fast neutron spectrum, molten salt reactors and, most recently, microreactors. For some near-term concepts, development is almost completed, while for other more innovative designs much work remains to be performed, including research and development (R&D), feasibility tests, full development of the safety case. However, a number of prototypes and demonstration innovative reactors are under development by several designers and vendors all over the world.

In the last decade the nuclear industry and an increasing number of Member States have focused their interest on a special category of advanced reactors, i.e. small modular reactors for near-term deployment. Many small modular reactors are envisioned for niche electricity or energy markets where advanced large reactors would not be viable. Small modular reactors are expected to fulfil the need of flexible power generation for a wide range of users and applications, including replacing aging fossil power plants, remote and off grid areas, providing cogeneration for electric and non-electric applications, enabling hybrid nuclear/renewables energy systems.

Trends

With the advent of powerful computing capabilities and data analysis tools, the nuclear industry is embracing artificial intelligence, machine learning and deep learning techniques for a wide range of visionary activities that could transform the way nuclear systems are being designed, licensed and operated. Artificial intelligence 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. Artificial intelligence 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. Artificial intelligence 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) have played a significant role in the commercial nuclear industry since its inception, currently accounting for more than 95% of all operating civilian power reactors in the world. As of the end of 2021, 48 out of 51 nuclear reactors under construction are cooled with light or heavy water.

Major developments in advanced WCRs in 2021 involve construction starts of an HPR-1000 reactor (Changjiang-3 in China), VVER-1200 (V-491) reactors (Tianwan-7 and Xudabao-3 in China), and a VVER (V-509) reactor (Akkuyu-3 in Türkiye), as well as new connections to the grid of an APR-1400 reactor (Barakah-2 in United Arab Emirates), an ACPR-1000 reactor (Hongyanhe-5 in China), a CNP-1000 reactor (Tianwan-6 in China), an ACP-1000 reactor (KANUPP-2 in Pakistan), and a PHWR-700 reactor (Kakrapar-3 in India).

Advanced versions of existing WCRs are also increasingly being considered, studied and implemented in several countries with the gradual deployment of advanced and more efficient fuel cycles.

Four countries (Canada, China, Japan and the Russian Federation) and the European Union are participating in joint R&D of supercritical water cooled reactor (SCWR) design concepts. The main purpose of the SCWR is to generate electricity efficiently, economically and safely. The majority of SCWR plants are developed for power generation higher than 1000 MW(e) at operating pressures of about 25 MPa and reactor outlet temperatures from 500°C to 625°C. As a consequence, SCWRs could generate electricity with thermal efficiencies ranging from 43% to 48%, which is significantly higher than those of the current fleet of nuclear reactor systems. The high core outlet temperature of SCWRs facilitates cogeneration, including hydrogen production, heating and steam production. Most SCWR concepts are developed for large baseload power generations of over 1000 MW(e), which are considered excessive for small remote communities, small mining operations and oil production. With a modular configuration, SCWR concepts can be scaled down to meet the needs of local deployment. The development of small and very small SCWR concepts has also been initiated; China is developing a 150 MW(e) concept for a demonstration plant. The conceptual designs of the Canadian SCWR, a heavy water moderated pressure tube reactor concept, and the Chinese CSR1000 were completed (Figure A.6).

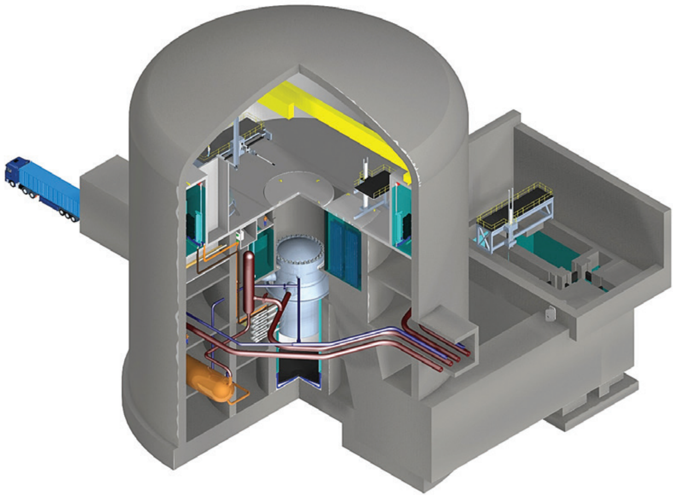


FIG. A-6. Canadian SCWR design — cutaway view of reactor building. (Image: Schulenberg and Leung, Canadian Nuclear Laboratories)

In Europe, the High Performance Light Water Reactor concept addresses the economic feasibility of a high efficiency LWR operating at supercritical water conditions with expected efficiency of ~44% and the targeted steam outlet temperature of 500 °C without exceeding available cladding material limits. The Russian Federation conceptual innovative water cooled, water moderated power reactors (VVERs) design with coolant at supercritical pressure also includes the possibility of a fast-spectrum core.

Trends

Most advanced WCRs have increased power outputs, with recent constructions varying from 1000 to 1700 MW(e) per unit, and further increases are targeted in the design phase of evolutionary large WCRs. Furthermore, a clear trend is towards multi-unit sites with a single or multiple reactor types, underscoring the economies of scale for commercial nuclear reactors. About 30 countries that currently have no operating NPPs are considering building them. For these newcomers, the first reactors are envisioned to be of the advanced water cooled type.

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

Status

Throughout 2021, many Member States have made tangible progress in SMR technology development for near term deployment. There are more than 70 small modular reactor designs of major lines of technologies under development for different applications.

In the Russian Federation, the Akademik Lomonosov floating NPP with two KLT-40S reactor modules has been in commercial operation since May 2020 following connection to the grid in December 2019, providing low-carbon power and heat to the port of Pevek. In China, the High Temperature Gas-cooled Reactor-Pebble-Bed Module (HTR-PM), was connected to the grid on 20 December 2021 (Figure A.7). The two reactor modules of HTR-PM achieved criticality in August and November 2021, respectively. The HTR-PM will generate 210 MW(e) as a demonstration plant. In Argentina, the CAREM-25 reactor, a prototype integral PWR (iPWR), is in an advanced stage of construction at the Néstor Carlos Kirchner NPP site, currently aiming for fuel loading and start-up commissioning in 2024 to produce 100 MW(th) and 34 MW(e) gross.

FIG. A-7. The HTR-PM in China was connected to the electricity grid on 20 December 2021. (Photo: Tsinghua University, Institute of Nuclear and New Energy Technology, China)

In July 2021, China started the construction of a 125 MW(e) ACP100 reactor, also known as Linglong One, at Changjiang in Hainan province. This iPWR is designed as a multipurpose small power reactor. In the United States of America, the Nuclear Regulatory Commission (NRC) issued the standard design approval (SDA) for the NuScale reactor standard design. The NuScale Power Module (NPM) is an iPWR with natural circulation. Construction of the NPM that comprises 6 modules of 77 MW(e) per module will begin in the next three years at a site near Idaho National Laboratory with operation date by 2029.

By the end of 2021, at least 16 Member States had established active national programmes on SMR design and technology development, most of which are carried out with international collaboration. In July 2021, Japan resumed the operation of its High Temperature Engineering Test Reactor (HTTR) that generates 30 MW(th) from its prismatic-bed reactor core. Earlier, the Republic of Korea and Saudi Arabia jointly completed the pre-project engineering phase for the system-integrated modular advanced reactor (SMART) that resulted in a preliminary safety analysis report for the 110 MW(e) iPWR. France progresses with the development of NUWARD, a 340 MW(e) (two 170 MW(e) reactors) iPWR type SMR with forced convection and advanced safety systems for potential deployment in foreign markets in the early 2030s. Likewise, the United Kingdom continued to work on developing technology for the UK SMR, a 470 MW(e) three-loop PWR-based SMR design for domestic and international deployment by 2030. In the Russian Federation, a decision was reached to start construction of the RITM-200N, a land-based iPWR to generate 50 MW(e), in Yakutia in 2024. Several units of RITM-200 reactors have been deployed in nuclear icebreaker ships. In Canada, the SMR Roadmap and Action Plan foresee possible applications of SMRs for on- and off-grid replacement of fossil and diesel generation plants, including in the oil and mining industries.

Trends

In 2021, development activities for a subset of SMRs known as microreactors also intensified in several countries, including Canada, the Czech Republic, Japan, the Russian Federation, the United Kingdom and the United States of America. Microreactors, from major technology lines, 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 engaged in the development of marine-based reactors. The Russian Federation has developed four SMR designs for floating power units and one design called SHELF for a subsea immersible power unit (Figure A.8). China has at least one design called ACPR100 to supply electricity for offshore oil and gas platforms. The Republic of Korea has also continued the development of BANDI-60, a PWR-based floating power unit.

The common developmental objective of SMRs is to demonstrate that reduced power and modularity will achieve lower upfront capital costs through economies of serial production, and that design simplification and short construction times lead to affordable financing schemes. To assist Member States in achieving a common understanding of their needs and specificities on SMR technology, the Agency has initiated a new framework for the development of generic user requirements and criteria (GURC) for small modular reactor design and technology. The key benefit of a national GURC document is to provide a set

FIG. A-8. The Akademik Lomonosov NPP with two KLT-40S reactors has been in commercial operation since May 2020, producing 70 MW(e) in Pevek, Russian Federation. (Photo: Rosatom's Afrikantov OKBM) of key policy, technical and economic requirements that will assist embarking countries in conducting reactor technology assessment and eventually developing a tender document. Successful deployment of SMRs in the next decade is expected to encourage more embarking countries to consider them and participate in relevant R&D.

A.4.3. Fast Reactors

Status

The Russian Federation continues to operate two industrial sized sodium cooled fast reactors (SFRs), BN-600 and BN-800, at Beloyarsk NPP and is designing the Generation IV SFR BN-1200 to be built at the same site. The Multipurpose Fast Research Reactor is under construction in Dimitrovgrad. The first concrete for the first lead cooled experimental and demonstration reactor, BREST-OD-300, was poured in Seversk in June 2021. China continued construction of a second SFR CFR-600 in Xiapu County, Fujian Province. In India, first criticality and commissioning of the 500 MW(e) sodium cooled Prototype Fast Breeder Reactor was expected in 2020 but was postponed. In 2021, TerraPower and GE Hitachi Nuclear Energy announced plans to construct an advanced hybrid Natrium reactor that features a 345 MW(e) SFR combined with a molten salt energy system to boost peak output to 500 MW(e) in Wyoming, USA (Figure A.9).

FIG. A-9. Bill Gates at TerraPower with a mock-up of a sodium cooled subassembly. (Photo: Gates Notes)

Trends

Sodium cooled fast reactors, with their proven technology and over 400 reactor-years of operation, constitute the majority of operational and newly built fast neutron nuclear energy systems. At the same time, heavy liquid metal coolant technology is attracting increasing attention, especially in the area of SMRs where several innovative designs are based on either lead or lead-bismuth eutectic cooled reactors. Other coolants, such as helium and molten salts are also considered as a promising technology by several countries in their innovative reactor conceptual designs. In general, fast reactors are believed to be a key component of the future sustainable nuclear energy, as any extensive developments of the nuclear power will require utilizing of the whole potential of natural uranium and/or thorium resources.

A.4.4. Non-electric Applications of Nuclear Power

Status

In 2021, a total of 61 operating nuclear reactors were utilized non-electric application (desalination, district heating and process heating) to generate over 2167 GW·h of electrical equivalent heat each year. Of these reactors, 48 supported district heating, three reactors supported industrial process heat, five supported both district and process heating, and five desalination.

The use of nuclear energy beyond electricity for other useful products is enjoying unprecedented interest worldwide, in particular because it offers the possibility to produce heat or hydrogen or other products without any carbon emissions. Nuclear heating technology has mature technical routes, broad market prospects and great development potential. Joining the group of experience users of district heating including Bulgaria, the Czech Republic, Hungary, Romania, the Russian Federation, Slovakia, Switzerland and Ukraine, China started providing district heating from the Haiyang nuclear plant in Shandong province in late 2020. Using heat provided by Haiyang units 1 and 2 (Generation III reactors of AP1000 technology) has enabled coal fired boilers to be replaced, leading to a reduction in the emissions of carbon dioxide of 180 000 tonnes annually. A district heating demonstration project was launched also at the Qinshan NPP in Zhejiang province, aiming to have a nuclear heating area of 4 million m2 by 2025, covering the main urban area of Haiyan County and the entire area of Shupu Town.

Hydrogen production using either electricity or heat from nuclear reactors is being considered by several countries. According to a recent scoping investigation using modelling work by the Agency, nuclear energy could be the most cost-effective means of producing clean hydrogen if gas prices remain well above the low levels seen over the past decades. This shift happens as natural gas costs reach $10–$15 per million British thermal units. This is a cost substantially lower than already observed in the second half of this year in the European Union, United Kingdom and parts of Asia.

France announced in October 2021 that, by 2030, it aims to start the construction of a small modular reactor and use other nuclear plants to produce clean hydrogen through electrolysis. The Russian Federation has chosen the Kola NPP site for a test to produce clean hydrogen through electrolysis. Also in 2021, the USA announced $20 million in funding to demonstrate the technology to produce clean hydrogen energy from nuclear power. This will support the goal of the Hydrogen Shot initiative launched this year to achieve a cost of $1 per 1 kg of hydrogen in one decade.

Trends

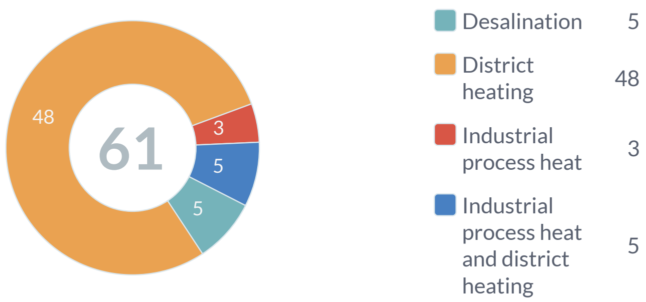
Emerging technologies such as SMRs and microreactors are focusing on systems with smaller power outputs which can provide applications beyond the electric grid, such as low-carbon heat for district networks, industrial process heat, hydrogen production and flexible power generation. Microreactors are particularly suitable for providing clean and cost-competitive energy to decentralized, off-grid markets. Of particular interest are the advanced reactor concepts capable of high temperature outputs which could significantly extend the opportunity for heat use. High temperature reactors (HTRs) are under development in several countries, with significant progress being made in Japan, and China recently started up its first HTR-PM unit in Shandong province.

over

2 167 GWh

electrical equivalent heat generated to support nuclear cogeneration

Number of nuclear reactors used for non-electric applications



A.4.5. Nuclear Fusion Research and Technology Development for Future Energy Production

Status

TThe ITER project is maintaining steady progress in machine and plant assembly despite unprecedented pressure due to the pandemic and the difficulties encountered in manufacturing some of ITER's first-of-a-kind components. Substantial progress has been made in the ITER machine assembly and integration, including the installation of the cylindrical lower cryostat thermal shield into the tokamak pit, welding of the first two cryostat sections, installation of the first two superconducting magnets in the tokamak pit, and the arrival on site of two toroidal field coils (from Europe and Japan) as well as of the first central solenoid module (from the USA), which will be assembled with six independent modules stacked in an 18-metre-tall structure (Figure A.10).

The 28th IAEA Fusion Energy Conference, held virtually during 10–15 May 2021, provided evidence of the quality of the theoretical, experimental, technological and materials development which is being conducted worldwide, and of the significant progress that has been achieved in the performance of the presently operating machines, including on some new devices which came online recently, namely JT-60SA in Japan, HL-2M in China and MAST-U in the United Kingdom.

Results from experiments conducted at the European JET tokamak, in preparation for the tritium and deuterium–tritium campaign, have provided ITER with important information for preparing its Disruption Mitigation System, as well as key results for plasma facing components and nuclear technology. Results from the analysis of experiments conducted at the optimized Wendelstein 7-X stellarator in Germany have confirmed that the energy losses of the plasma are reduced, which gives confidence that the disadvantages of earlier stellarator designs can be overcome and that stellarator-type devices might also be suitable for power plants. Results from the United Kingdom Atomic Energy Authority's (UKAEA's) new MAST-U experiment at the Culham Centre for Fusion Energy have demonstrated the effectiveness of an innovative heat exhaust system designed to make compact fusion power plants commercially viable. The new system, known as a 'Super-X divertor', would allow components in future commercial

FIG. A-10. The 110-tonne ITER central solenoid module is loaded into the hold of a general cargo vessel to be shipped from the USA to the ITER site in France. The five-storey tall, 1000-tonne central magnet will induce 15 million amperes of electrical current in ITER's plasma to initiate each plasma pulse and to provide vertical stability of the plasma. To accomplish this, the central solenoid will reach a magnetic field strength of 13 tesla, about 280 000 times stronger than the Earth's magnetic field. (Photo: US ITER)

tokamaks to last for much longer, increasing the power plant's availability, and improving its economic viability. The Divertor Tokamak Test (DTT) facility, under construction at the Frascati site of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, over the next decades will also test different divertor geometries and compare them in a high outflowing power density plasma, as similar as possible to a real burning plasma.

The Kurchatov Institute in the Russian Federation celebrated the start of operation of the upgraded tokamak T-15MD (Figure A.11). The research programme on the T-15MD tokamak will be aimed at solving the most pressing problems of ITER. Experiments at the USA's Lawrence Livermore National Laboratory's National Ignition Facility have made a significant step toward demonstrating fusion energy production, achieving a fusion energy yield of more than 1.3 megajoules.

One of the key elements in the development of fusion as a commercially viable source of energy is the setup of an adequate safety and regulatory framework for fusion devices. During 2021, a number of initiatives towards the establishment of a specific regulatory framework for fusion at the national level have started in China, Europe, the United Kingdom and the USA. The Agency has also started to gather all available information in the field to provide guidance and best practices at the international level, with the final goal of fostering harmonization of the regulatory frameworks for fusion.

Trends

The establishment of fusion enterprises supported by private capital has been accelerating over the past seven years. New companies can be found all over the world, mostly in the Member States that belong to the ITER project (China,

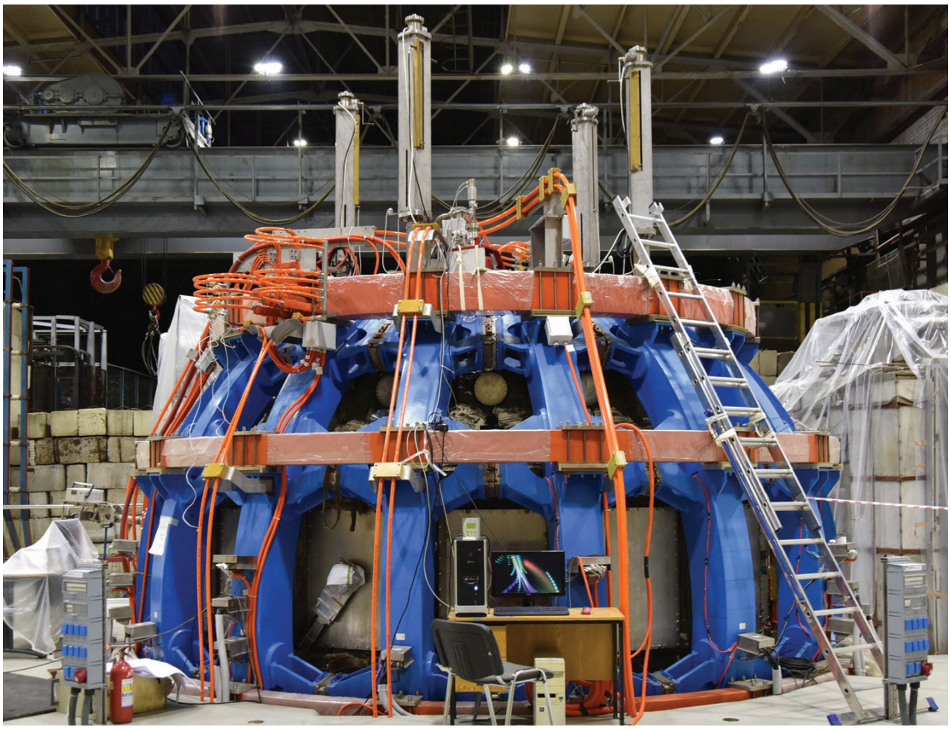


FIG. A-11. The T-15MD tokamak is water cooled and capable of creating a toroidal magnetic field at the plasma axis of 2 T; it will also be equipped with powerful additional plasma heating systems with a total power input into the plasma of up to 20 MW, and modern engineering infrastructure. The current in the plasma should reach 2.0 MA with a duration of 10 s. The T-15MD tokamak was built over ten years and its experimental programme will contribute to ITER's and future fusion power plants' operation. (Photo: Kurchatov Institute)

European Union, India, Japan, Republic of Korea, Russian Federation and United States of America, as well as in the United Kingdom). In addition, at the University of New South Wales, Australia, a spin-out start-up was founded in 2020. The model of public–private funded partnerships launched in the USA has proven to be very successful and other Member States are exploring to replicate this scheme. An overview of all fusion public and private devices with experimental and demonstration designs, which are currently in operation, under construction or being planned can be found in the Fusion Device Information System[1] (Figure A.12).

The UKAEA has launched an ambitious initiative to demonstrate the ability to generate net electricity from fusion by 2040, which will involve building the Spherical Tokamak for Energy Production (STEP). This plant will provide knowledge and experience in maintenance through the whole operational life of the facility and fuel self-sustainability. It is foreseen to approve the concept design of STEP by 2024 that in its first phase will be a spherical tokamak connected to the national grid and producing net energy but not for a commercial purpose. £222 million (€264 million) have been allocated to begin the STEP design work. Currently, different locations within the United Kingdom are being studied, with a final decision expected by the end of 2022 (Figure A.13).

[1] https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx

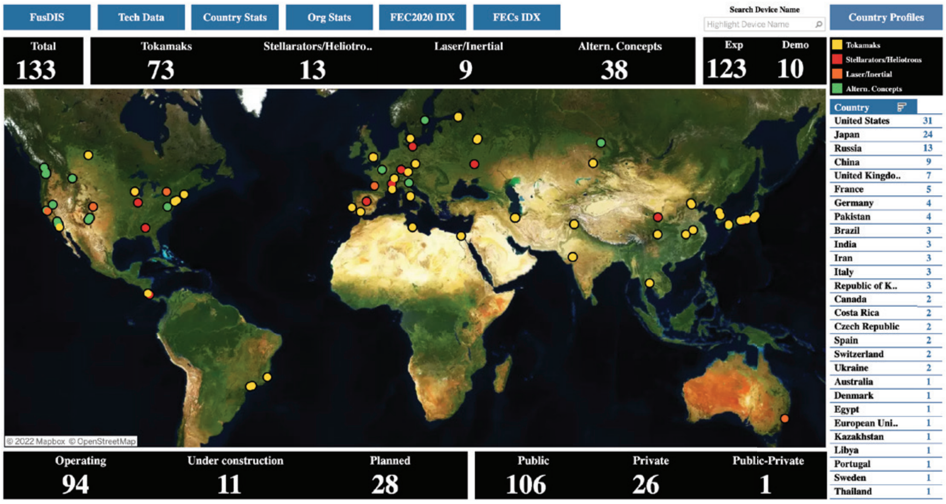


FIG. A-12. Over 130 experimental, public and private, fusion devices are operating, under construction or being planned, while a number of organizations are considering designs for demonstration fusion power plants. (Source: IAEA Fusion Device Information System)

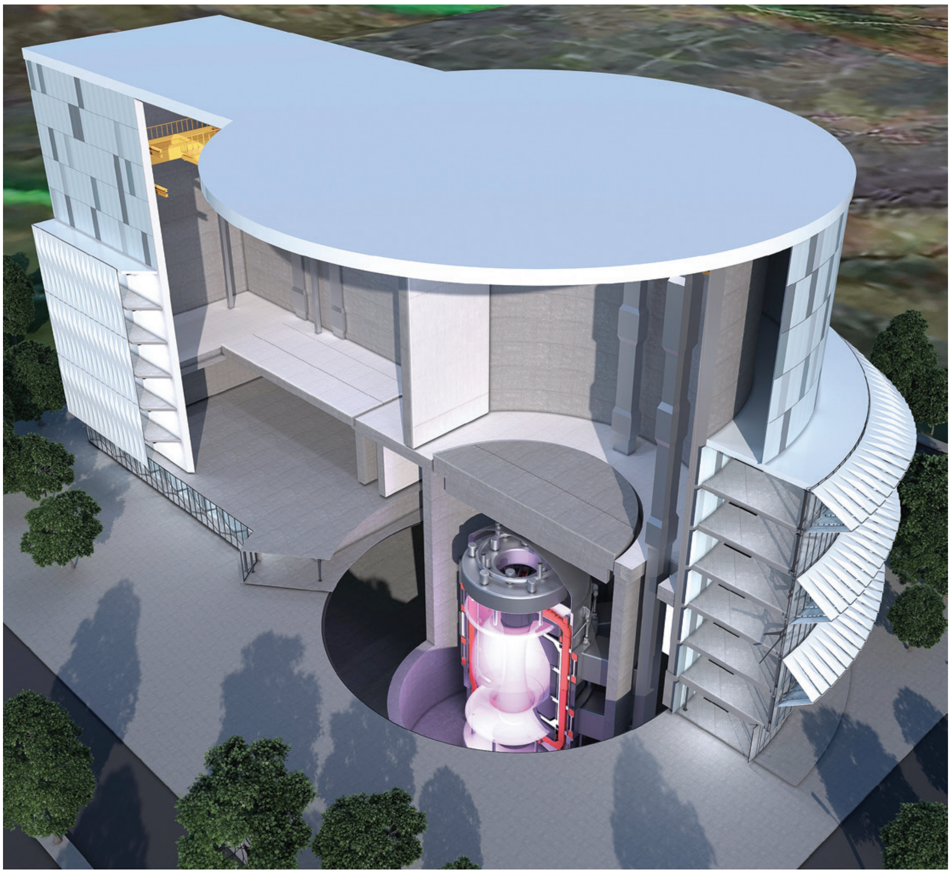
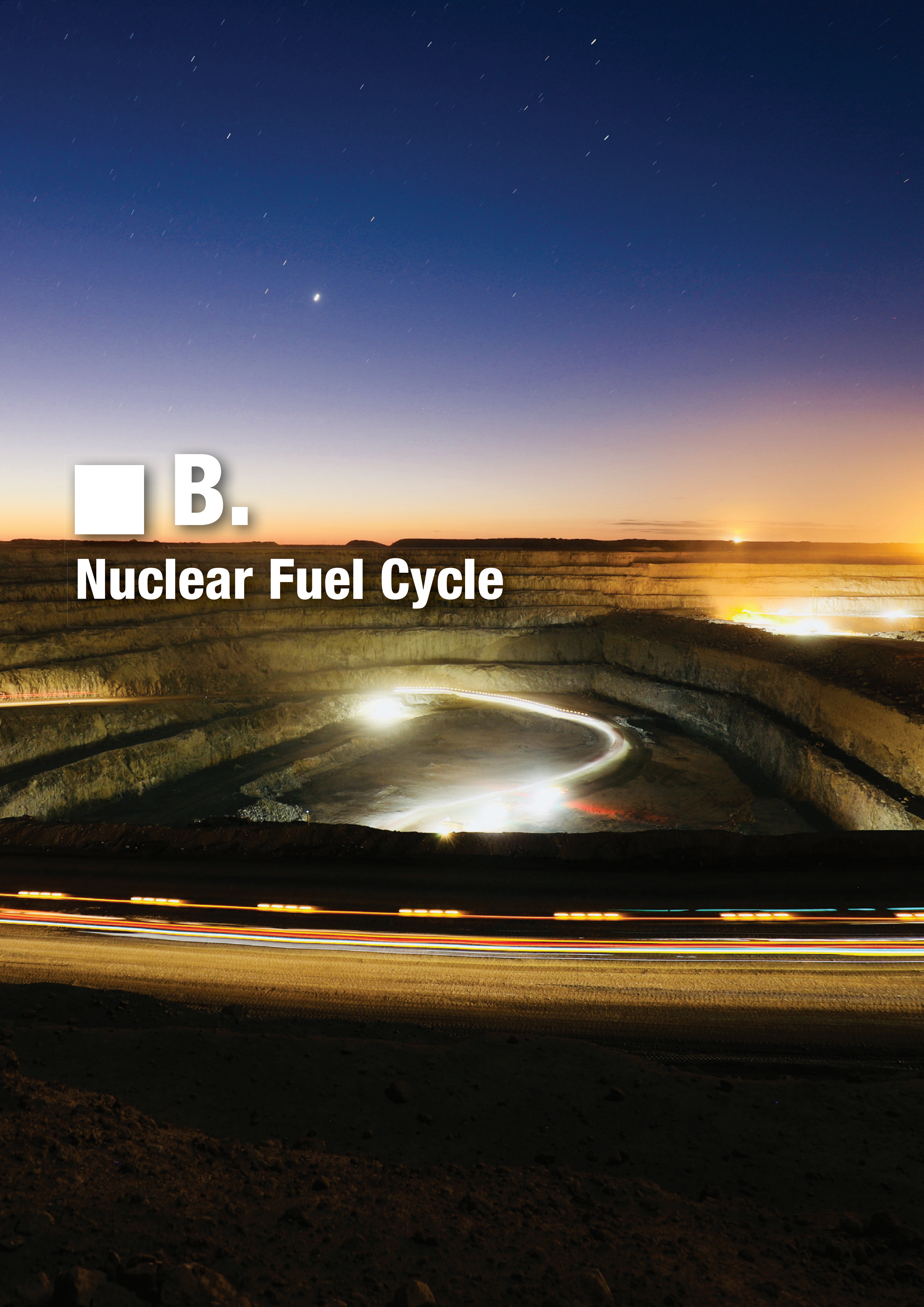


FIG. A-13. View of the planned STEP building. (Image: UKAEA)



B.

Nuclear Fuel Cycle

B. Nuclear Fuel Cycle

B.1. Front End

Status

In the first quarter of 2021, the uranium spot price was about $26.50/lb U_3O_8. Sustained prices at this level forced several primary producers to keep their operations in a state of care and maintenance or at reduced production rates[2]. Since 2011 there has been an oversupply of uranium on the market; however, due to consistent demand for uranium for nuclear fuel and reduced primary production, global inventories of U_3O_8 have steadily decreased in response to the sustained low market prices. The trend in inventory reduction was evident in 2020 and 2021.

The sustained downturn in global primary production through 2020 and into 2021 has exposed the fragility of the uranium market. This has prompted several investors, funds, traders and primary uranium producers to purchase U_3O_8 on the market in response to the forecasted shift in the supply-demand for U_3O_8. For example, Kazatomprom announced in October 2021 its intention to participate in a physical uranium fund (named ANU Energy), which will hold physical uranium as a long term investment. Such purchases of U_3O_8 by a diverse number of non-nuclear utility actors globally have not been observed in the past in the uranium markets. As a result of reduced inventories and the accelerated trading of U_3O_8 in 2021, the spot price in late October 2021 had increased by 74% to about $46.00/lb U_3O_8 since the first quarter of 2021.

Nuclear fuel production is a mature technology, which has continuously improved over the years through automation and digitization, reduced operational waste generation, enhanced radiation protection for workers, as well as reduced fuel failures in reactors. Existing nuclear fuel fabrication capacities are sufficient worldwide to cover anticipated nuclear power demand, and good progress is being made to demonstrate the safe behaviour of new advanced technology fuels (ATFs) designed for irradiation in current and next generations of nuclear power reactors, including SMRs (e.g. Framatome's GAIA design including PROtect Enhanced Accident Tolerant Fuel as well as Global Nuclear Fuels' and Westinghouse's accident tolerant fuel concepts that consist of coated zircaloy cladding and doped UO_2 pellets, TVEL's TVS-2M model with chromium-coated zirconium cladding and Cr-Ni alloy, Rosatom's REMIX fuel designed to multi-recycle uranium and plutonium in light water reactors (LWRs), and Clean Core's Advanced Nuclear Energy for Enriched Life (ANEEL) fuel technology using a combination of thorium and high assay low enriched uranium (HALEU) for a much-improved fuel performance in CANDU reactors).

The UK National Nuclear Laboratory (NNL) has estimated several ATF designs from the point of view of maturity, economics and safety.

Trends

Uranium exploration expenditure has been steadily decreasing since 2012 as a result of sustained low uranium prices, which was further impacted by the

[2] Another major uranium producer, Kazatomprom in Kazakhstan, announced a 20% reduction in production from its in situ recovery mines with this reduction in production sustained through 2021.

COVID-19 pandemic from early 2020. Recent increases in the uranium market price have incentivized some investments with some renewed exploration and development activity in 2021 as well as restarting of some primary production.

The sharp increase in the spot price of uranium in 2021 has prompted some operators[3] who had uranium mines and processing facilities in care and maintenance to investigate restart plans. A further decrease in global U_3O_8 inventories and a sustained increase in the spot price for uranium may incentivize other uranium mines and processing facilities that are in a state of care and maintenance to restart their operations and new uranium projects to be developed for commercial purposes or domestic security of supply[4].

Innovation is required to advance marginal uranium deposits into production. An ongoing example of such innovation in the uranium mining industry in 2021 was the positive results achieved in the feasibility studies for development of an in situ recovery mine in a high-grade unconformity type deposit. Bioleaching methods are another significant innovation being developed for application in in situ recovery of uranium from sandstone type deposits.

Since 2011, international efforts have focused on improving the safety and performance of fuels used in existing LWRs. Other drivers for nuclear fuel development are innovative reactor designs, like Generation IV reactors and SMRs (ranging from scaled down versions of LWR fuel designs to entirely new Generation IV fuel designs), some of them having reached demonstration scale (such as HTR-PM in China); and improving the economics and the sustainability of nuclear power (elongation of fuel irradiation cycles, higher burnups, zero defect campaigns, innovative methods for fuel manufacturing, new fuel cycles, and multiple recycling of nuclear materials from spent nuclear fuel). HALEU is required for manufacturing many innovative nuclear fuel concepts, like ATFs or SMR fuels.

[3] For example, the Langer Heinrich uranium mine in Namibia announced in October that it is working on the critical path elements required for restarting its idled uranium mine and processing facility.

[4] One example is the Badrakh Energy project in Mongolia, which announced in July that it began pilot testing at its Zuuvch Ovoo deposit. Further, in July, the Jordan Uranium Mining Company announced that its demonstration plant has been fully commissioned and has the capacity to process 70 tonnes of ore per annum. Results from these tests will be used to evaluate the technical, environmental and economic feasibility of these deposits and whether they will advance to full-scale production.

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 about 300 000 t HM. For countries with long established nuclear programmes pursuing open cycle strategies, the main challenges are the need for additional SNF storage capacity as well as the increasing storage duration (100+ years).

SNF is moved from wet to dry storage after an initial cooling time. As reductions in those initial cooling times are becoming more common, dry storage systems require improved heat removal capabilities[5]. New centralized storage facilities have been licensed in Ukraine and the United States of America. SNF is transported in some countries and measures towards improving transportation are routinely implemented. Member States are continuing with the removal and relocation of their spent nuclear fuels in the framework of the decommissioning projects of their NPPs. Researchers in the Czech Republic have developed and patented an innovative technology named Teplator to benefit from the radioactive decay heat produced by spent fuel to heat water[6].

Movements towards recycling implementation are foreseen: in France, it is a mature industrial scale activity; in Japan, the Federation of Electric Power Companies (FEPC) plans to use MOX fuel in at least 12 units by 2030[7]; in the Russian Federation a pilot demonstration facility at the Mining and Chemical Combine in Krasnoyarsk, to trial new spent nuclear fuel reprocessing technologies for their subsequent large scale deployment is in the final stages of construction[8]; in the USA, Oklo and Argonne National Laboratory have teamed up to conduct research and development of electrorefining technology to recycle fuel for use in advanced fission power plants[9].

In several countries (e.g. China, France, Japan, Republic of Korea, Russian Federation), R&D projects continue to study the selective partitioning of minor actinides for their further transmutation in fast reactors and/or subcritical systems so as to minimize the burden of high level nuclear waste.

The UK NNL released its roadmap outlining the role of advanced fuel cycle developments in supporting nuclear in a low carbon energy future.

Trends

Understanding the behaviour of SNFs in various storage systems and the ageing and degradation mechanisms of storage structures, systems and components remain vital in ensuring that SNFs can continue to be stored safely and subsequently transported to disposal or reprocessing facilities. The Agency coordinates research activities on this matter to collect Member States' operational experience and foster information sharing.

Efficiency gains in the management of nuclear reactors have resulted, over time, in less SNF being discharged from nuclear reactors, but the trend towards higher initial enrichments and higher burnups results in greater residual heat and higher cladding embrittlement risks, which may impact SNF management steps.

Research will be needed to manage SNFs based on new designs (e.g. evolutionary ATFs, and HALEU fuels) with higher uranium-235 enrichments (up to 20%) and with new cladding materials, in particular in relation with higher heat loads and potentially different fuel behaviours in the longer term. Centralized

[5] In May, the final spent fuel assemblies from the Oyster Creek NPP were placed into dry storage 32 months after the reactor was permanently shut down, representing a record defuelling rate. The cask loading campaign was completed safely within a period of 21 weeks.

[6] In April, researchers from the Czech Technical University in Prague and the University of West Bohemia in Pilsen presented a patented innovative solution that uses the radioactive decay heat produced by spent fuel rods for water heating.

[7] In February, the FEPC revised Plutonium Utilization Plan, based on the latest Operational Plan for the Rokkasho Reprocessing Plant and the MOX Fuel Fabrication Plant, and changes in the business environment in the past year.

[8] Additionally, in the Russian Federation, work is under way to build infrastructure to demonstrate the closure of the nuclear fuel cycle with fast reactors, since 2017 the industrial production of MOX fuel for the BN-800 fast reactor has been under way in the Russian Federation, nuclear fuel for RBMK and VVER reactors is manufactured using regenerated uranium.

[9] In June, the US Department of Energy awarded funding to Argonne National Laboratory to commence research and development of electrorefining technology to recycle fuel for use in advanced fissions power plants. The funding was matched by Oklo.

storage facilities could be one solution in the near future to accommodate spent fuel from shut down power reactors to enable full site decommissioning and remediation.

Advanced processes for plutonium multi-recycling (REMIX in Russia, CORAIL and MIX in France) in LWRs are currently undergoing demonstration tests to enable the transition to plutonium multi-recycling strategies in fast reactors in the future.

There is increased interest in developing SMRs based on different designs to be deployed in the next decade or so, for which safe, secure and sustainable associated fuel cycle development will be needed.

This effort applies to the continuous efforts in progressing towards the implementation of advanced reactors for which safe, secure, and sustainable associated advanced fuel cycles will be needed.

C.

Decommissioning, Environmental Remediation and Radioactive Waste Management

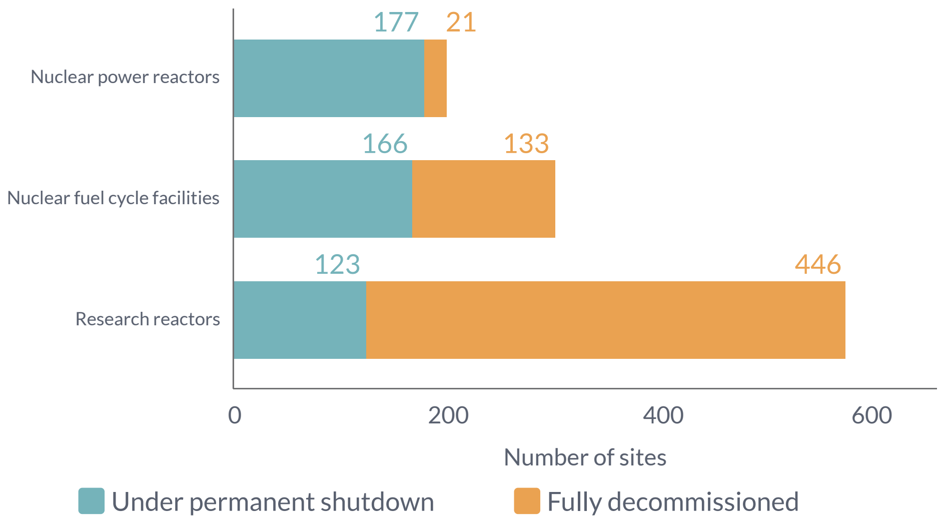
C. Decommissioning, Environmental Remediation and Radioactive Waste Management

C.1. Decommissioning

Status

Five nuclear reactors were permanently shut down in 2021: Dungeness B1 and B2 in the United Kingdom, Indian Point-3 in the USA, KANUPP-1 in Pakistan, and Kuosheng-1 in Taiwan, China. This is broadly in line with the rate of permanent reactor shutdowns over the past decade, during which time 57 reactors were retired from service (of which 18 reactors in Japan and 12 in the USA). The closures of Dungeness B1 and B2 represent the first of the United Kingdom's advanced gas cooled reactor fleet to be permanently shut down, with the remainder of the fleet expected to follow by the end of the current decade. The KANUPP-1 CANDU-type reactor is the first of the Pakistan reactor fleet to be permanently shut down.

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



In November 2021, the licence for Humboldt Bay NPP unit 3 in California, USA, was terminated with the site being released for unrestricted use. With this, the number of fully decommissioned nuclear power reactors reached 21, with a further 177 reactors, making up approximately 28% of the global reactor fleet[10], under permanent shutdown or currently under decommissioning. In addition, 166 nuclear fuel cycle facilities are in permanent shutdown or under decommissioning, and 133 facilities have been fully decommissioned. Furthermore, 123 research reactors have been permanently shut down or are currently under decommissioning, and 446 research reactors have been

[10] The global reactor fleet comprises 442 reactors (69%) in operation, 177 reactors (28%) under permanent shutdown, and 21 reactors (3%) fully decommissioned.

fully decommissioned. The main ongoing power reactor decommissioning programmes are in Germany with 27 reactors under permanent shutdown or currently under decommissioning; Japan with 26 reactors under permanent shutdown or currently under decommissioning; and the USA with 25 reactors under permanent shutdown or currently under decommissioning.

Progress is being made on those nuclear reactor sites which suffered major accidents, including Fukushima Daiichi NPP in Japan, which suffered an accident following the Great East Japan Earthquake in 2011 (Figure C.1). Work to remove spent fuel from the spent fuel pools at Fukushima Daiichi Units 1–4 continues on schedule, with the current focus being on Units 1 and 2 (Units 3 and 4 have already been completed). A significant milestone was also achieved at the damaged Unit 4 of Chornobyl NPP in Ukraine when the New Safe Confinement received a licence for operation in August 2021 (Figure C.2). The decommissioning of the Three Mile Island Unit 2 in the USA was transferred to a specialist decommissioning consortium in December 2020; decommissioning of the damaged facility has now begun and is scheduled to be completed by 2037.

FIG. C-1. Management of spent fuel at the Fukushima Daiichi NPP.

As regards decommissioning activities at fuel cycle facilities, an important precursor to facility dismantling is generally the removal of legacy wastes, typically stored in ponds or in concrete trenches. Significant progress on this aspect of decommissioning continues to be made at major facilities, including the removal of sludges from legacy fuel storage ponds at Sellafield in the United Kingdom; the removal of legacy graphite and magnesium waste stored in concrete silos at La Hague in France; the demolition of buildings and removal of base concrete slabs at the Oak Ridge Gaseous Diffusion Plant in the USA; and the demolition of several radioactively contaminated buildings previously used by the radiochemical plant of the Mayak Production Association in the Russian Federation.

Research reactors under decommissioning are primarily located in France, Germany, Japan, the Russian Federation, the United Kingdom and the USA. Several research reactors decommissioning projects are ongoing in Scandinavia. An important milestone was reached during 2021 at the FiR-1 reactor in Finland when the irradiated fuel from the reactor was transported to the USA. Another

FIG. C-2. At a ceremony on the 35th anniversary of the Chernobyl nuclear accident, Director General Rafael Mariano Grossi pays respect to victims in front of the New Safe Confinement.

example of progress is the Japan Atomic Energy Agency Oarai Research & Development Institute in Ibaraki Prefecture, where the decommissioning plan of the Japan Materials Testing Reactor (JMTR) was approved in March 2021. The entire dismantling schedule has been divided into four stages, and the first stage of dismantling has begun.

Trends

Many of the issues which have led to the shutdown of nuclear facilities over the past decade — political and economic factors, maintenance and/or refurbishment costs, and electricity market conditions — are expected to continue to apply in the future, and indeed the rate of shutdowns may accelerate due to the age profile of the current fleets, partly compensated by lifetime extensions. A large majority of the approximately 300 nuclear power reactors which are currently 30 years old or more may be retired from service over the next three decades. A similar development is anticipated in the case of research reactors as this fleet has a broadly similar age profile.

There is an increasing trend in favour of early dismantling of facilities once they have been permanently shut down. The selection of an immediate dismantling strategy is typically influenced by government policy, for example France and Germany have implemented policies that strongly favour this approach. Cost uncertainties for projects occurring in the distant future are also likely to be a significant factor for facility owners, many of whom prefer to avoid carrying long term liabilities with high levels of uncertainty. This appears to be a strong driver for the current trend in the USA away from deferred dismantling strategies.

Deferred dismantling has historically been the preferred strategy for graphite moderated reactors, due to the lack of generally accepted strategies for the long term management of irradiated graphite, and also because such reactors are typically much larger than water moderated reactors and therefore dismantling activities have a significantly higher level of complexity. However, even for such reactors, current trends appear to be favouring a more immediate dismantling approach. For example, the United Kingdom's Nuclear Decommissioning Authority has decided to adopt a site-specific decommissioning strategy for each of its Magnox reactor sites, with the Dungeness A and Trawsfynydd reactors proceeding with early dismantling on a 'lead and learn' basis. Ignalina NPP is proceeding with the immediate dismantling of its facility, including development of a storage facility for irradiated graphite pending the development of a long term geological disposal facility in Lithuania.

C.2. Environmental Remediation

Status

Environmental remediation encompasses solutions to address contamination of land areas (soil and groundwater) caused by inappropriate management practices adopted in the past. Legacy sites can include nuclear sites (involving redundant research and fuel cycle facilities), former nuclear test sites, sites affected by past uranium mining and processing operations as well as by other activities involving the use of naturally occurring radioactive material (NORM), or sites affected by major nuclear or radiological accidents. The nuclear industry has left a footprint in 31 countries, not including uranium mining and processing sites.

In most of these countries the footprint is rather small; however, there are some countries with long-established nuclear industries, encompassing both the civilian and military sectors, where nuclear operations, including electricity generation, reprocessing and experimental processes, are intermixed with redundant facilities, nuclear waste and legacy sites. Nevertheless, land contamination through nuclear operations in Europe, for example, accounts for only 0.1% of contaminated land in the continent. Worldwide, there is greater recognition that sites affected by NORM related industries need to be addressed.

In the USA, 2020 saw the start-up of the Savannah River Salt Waste Processing Facility and the completion of decontamination and decommissioning activities at the East Tennessee Technology Park in Oak Ridge. In 2022, the Department of Energy's Office of Environmental Management is expected to deal with chromium groundwater contamination at Los Alamos National Laboratory and to complete targeted buried waste exhumation at the Idaho National Laboratory site.

In Japan, decontamination activities resulting from the Fukushima Daiichi NPP accident continue apace. The whole area decontamination in the Special Decontamination Area was completed as planned. The decontamination conducted by the municipalities in the Intensive Contamination Survey Area was also completed. This means that the whole area decontamination based on the Act on Special Measures Concerning the Handling of Radioactive Pollution was completed, excluding the Restricted Area. The air dose rates in the environment have been continuously decreasing. As of the end of April 2021, approximately 10 730 000 m3 of removed soil and waste had been transported to the Interim Storage Facility (ISF). Almost all of the removed soil is expected to be delivered to the ISF by the end of March 2022.

Trends

In some countries, remediation is stagnant due to a lack of resources. Therefore, financing of remediation constitutes a key challenge. Led by the European Union, the international community established the Environmental Remediation Account for Central Asia. A funding gap needs to be closed to finance urgent work addressing the former uranium mining legacy sites in the region. As of September 2021, the gap was estimated to be €40 million. Relying on public funds alone, however, may not be enough to shoulder all remediation actions needed. Therefore, one important challenge is the establishment of creative new financial mechanisms for remediation, especially those initiatives that can lead to the mobilization of private capital.

There is a trend towards inclusive decision-making mechanisms, but there is a need to clarify the roles and responsibilities of actors and to enhance coordination; engage in dialogue with local stakeholders to better address the notion of affected territory/community; and anticipate the related management protocols. Citizen science can be taken as the practice of public participation and collaboration in scientific research to increase scientific knowledge. Among other things, it enables people to monitor their own homes and environments and impacts people's relationship with government and other key institutions. National and international organizations need to be prepared to deal with the process of policy- and participatory decision-making.

C.3. Radioactive Waste Management

Status

In 2021, Australia's Government announced plans for the national nuclear waste storage facility to be located in Napandee, South Australia. The facility will permanently dispose of low level radioactive waste and temporarily store intermediate level waste. Similarly, there is a process under way in Italy to identify suitable areas for a national repository for the disposal of 78 000 m3 of very low level waste and low level waste, and the long term interim storage of approximately 17 000 m3 of intermediate level waste and high level waste. The repository will be a near surface facility with a technology park for the development of research activities in the nuclear field.

Some Member States made significant steps in 2021 towards the final stages of disposal at their low level waste facilities. In Slovakia, the final cover for very low level waste at the Mochovce disposal facility has received approval. In the United Kingdom, preparatory work was carried out this year to allow for cover placement over the waste in Vault 8 and part of the trenches at the Low Level Waste Repository site. Furthermore, it is also being considered whether the site could be used to host a near surface disposal facility and site investigations of the underlying bedrock are currently being undertaken (Figure C.3).

Significant progress can also be noted towards the implementation of deep geological repository (DGR) programmes for high level waste. For instance, the Finnish waste management organization Posiva submitted a licence application for operations in December 2021, and plans for first spent fuel disposal in the Onkalo DGR by mid 2023. The Swedish Nuclear Fuel and Waste Management Company is waiting for a government decision to begin construction and underground confirmation studies at the site proposed for its DGR. The French National Radioactive Waste Management Agency is expected to submit its

FIG. C-3. Preparatory work at LLWR (UK) to support final cover placement over part of the facility. (Photo: UK Nuclear Decommissioning Authority, 2021).

construction licence application for a deep geological disposal facility for high and intermediate level waste in 2022. The Swiss National Cooperative for the Disposal of Radioactive Waste and the Canadian Nuclear Waste Management Organization have also started activities related to site selection to host a DGR for spent fuel.

Progress in these Member States has come after many decades of R&D, primarily carried out in underground research facilities (URFs). Presently, there are 13 operating URFs. China started construction of the Beishan underground research laboratory in June 2021 and opened the future URF research, development and demonstration programme to international cooperation as an Agency Collaborating Centre for geological disposal.

Significant progress for the management of disused sealed radioactive sources, specifically in terms of retrieval and conditioning, was made in 2021. In Jordan, legacy disused radioactive sources from an underground storage pit were retrieved and conditioned in new waste packages (Figure C.4).

FIG. C-4. Retrieval and conditioning of radioactive sources in new waste packages at a legacy waste storage site in Jordan. (Photos: Jordan Atomic Energy Commission)

Trends

A notable number of Member States initiated or relaunched the development of a national policy and strategies for radioactive waste management over the past few years with significant progress being made during 2021. Throughout the year, the Canadian Government engaged with the public, including indigenous peoples, stakeholders and experts, to review and modernize Canada's radioactive waste policy. In the United Kingdom, the Low Level Waste Repository company became a direct subsidiary of the Nuclear Decommissioning Authority (NDA) in July 2021, in line with the NDA's new national strategy for dealing with existing and projected decommissioning wastes.

There is a growing need for expansion of radioactive waste storage and disposal capacity for all types of radioactive waste and this trend is expected to accelerate as more NPPs are planned for decommissioning over the next decade. To address this need, a number of licence applications and new constructions are being carried out. For example, the Republic of Korea's Nuclear Safety and Security Commission approved the construction of additional capacity for the interim storage of spent fuel at the Wolsong NPP in 2020 as the existing spent fuel facility is nearing full capacity.

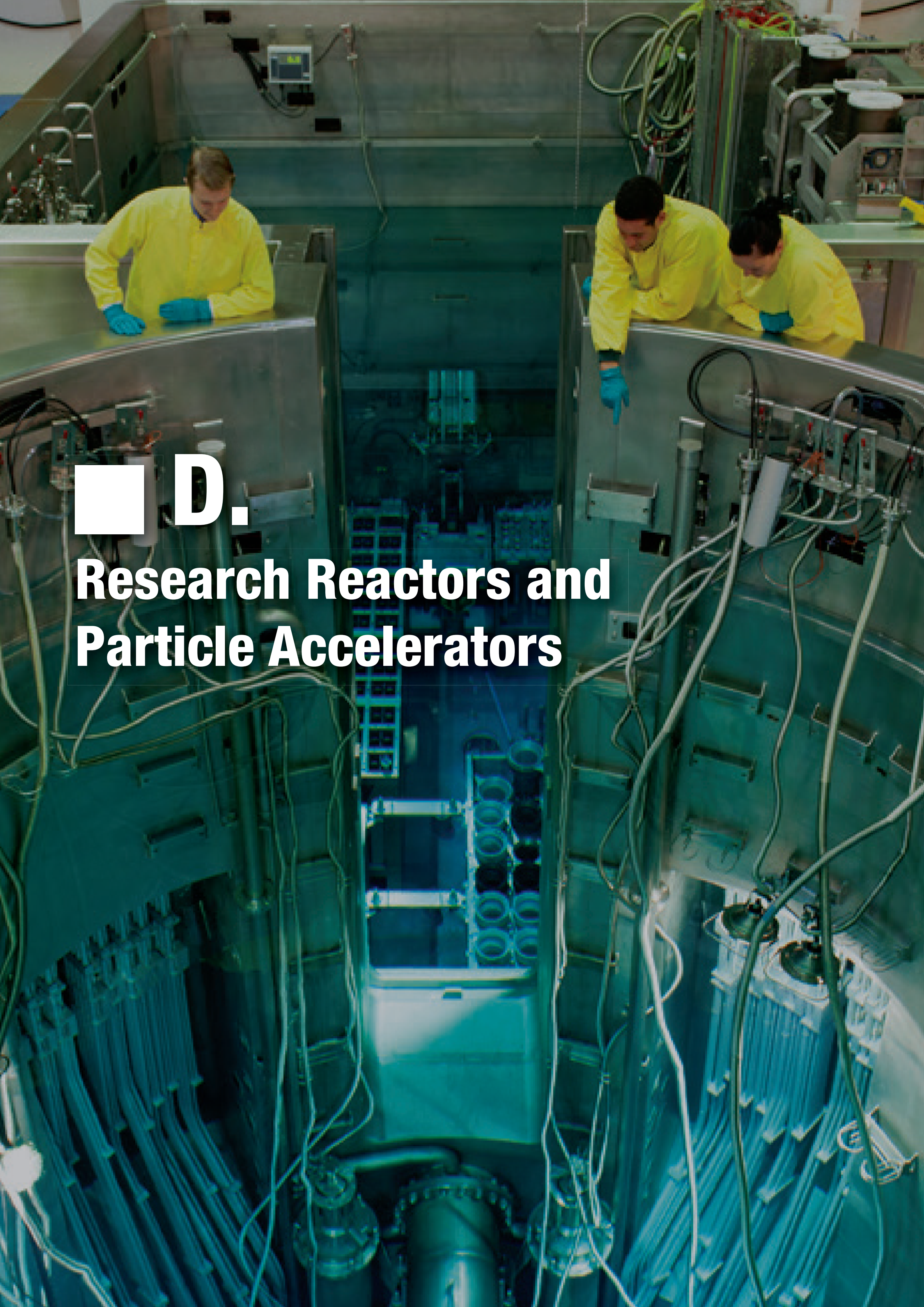
The past few decades have also shown a steady increase in attention paid to continuous and well considered engagement with the public. As a result of the COVID-19 pandemic, Member States carried out a lot of stakeholder involvement work using virtual means, resulting in a broader outreach (for example, the national seminar supporting the siting process of the national repository taking place in Italy was broadcast online).

While many countries have made progress with respect to the management of disused sealed radioactive sources (DSRS), disposal of DSRS is still a challenge, especially in countries with smaller nuclear programmes. Malaysia is planning to implement the first borehole disposal for DSRS in 2022. An increase is being observed in the return of disused high activity sources to suppliers for recycling and disposal. Over 50 high activity sources are planned to be removed from over a dozen Member States in 2022.

International collaboration continues to expand in the field of radioactive waste management, especially for deep geological disposal programmes. The European Union's Implementing Geological Disposal of Radioactive Waste Technology Platform, launched in 2009, continues to actively pursue its Vision 2025 Report, which details the vision of having the first geological disposal facilities for spent fuel, high level waste, and other long lived radioactive waste operating safely in Europe by 2025. At the same time, ERDO, formerly known as the European Repository Development Organisation and since 2021 established as the Association for Multinational Radioactive Waste Solutions, continues work on exploring the implementation of one or more shared geological repositories in Europe.

D.

Research Reactors and Particle Accelerators



D. Research Reactors and Particle Accelerators

D.1. Research Reactors

Status

There were 235 operational research reactors, including those in temporary shutdown, in 53 countries at the end of 2021. 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 D-1 in the Annex.

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

14
Member States have formal plans to construct new research reactors

16
countries are considering building research reactors

Eleven new research reactors 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 (Figures D.1a, D.1b and D.1c). In 2021, first concrete was poured for the first research reactor in the Plurinational State of Bolivia, and the PIK reactor in the Russian Federation entered the final stage of commissioning tests. South Africa made formal plans to construct a new research reactor — the Member States that currently have such plans are 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. To date, 6826 kilograms of HEU have been repatriated to their country of origin or otherwise dispositioned from 48 countries (and Taiwan, China). Additionally, 107 research reactors and major medical isotope production facilities have been converted from the use of HEU to low enriched

FIG. D-1 a. Construction of the RA-10 research reactor at Ezeiza Atomic Centre in Argentina. (Photo: CNEA).

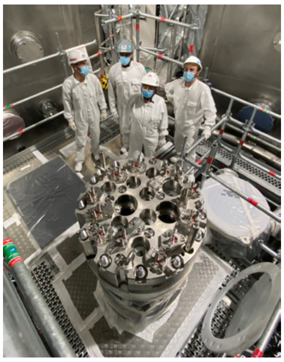


FIG. D-1 b. Installation of the closure head of the Jules Horowitz Reactor in Cadarache, France. (Photo: CEA).

FIG. D-1 c. Installation of floor slab in the base of the MBIR reactor cavity, Research Institute of Atomic Reactors State Scientific Centre, Dimitrovgrad, Russian Federation. (Photo: Rosatom)

uranium (LEU) or confirmed as being shut down. Extensive R&D work is carried out for the development of new high density LEU fuels for high performance research reactors. The Institute for Radioelements in Belgium remains on track to achieve full conversion to LEU for molybdenum-99 production in 2022, at which point all global producers of this highly demanded medical isotope will be using non-HEU production methods. The US Department of Energy National Nuclear Security Administration competitively awarded three new cost-shared cooperative agreements to private companies for commercial-scale production of non-HEU molybdenum-99 by the end of 2023.

Trends

The share of research reactors operating for at least 50 years is approaching 50 per cent. To ensure their continued safe and reliable operation and enhanced utilization, many facilities have established, or are in the process of establishing, proactive strategies and systematic ageing management, refurbishment and modernization. Some organizations operating highly utilized research reactors are preparing or considering the extension of their active lifetime to 80 or even 100 years (Figure D.2). One of the most common examples is the replacement of obsolete analogue instrumentation and control systems by new digital systems.

Many countries take advantage of opportunities to access research reactors through international and regional collaboration initiatives. In 2021, two Internet Reactor Laboratories with host reactors in the Czech Republic and the Republic of Korea started transmissions of experiments to students in other countries, and the European Nuclear Experimental Educational Platform was launched, offering practical training at small research reactors to universities and young nuclear professionals from all over the world.

Neutron scattering is used worldwide to address a number of challenges including in health and life sciences to provide information on biological function, including viruses, proteins and degenerative diseases, and to assist in the development of new drugs and therapeutic approaches. It contributes to understanding processes relevant to production, pollution, purification and conservation of food and water. It plays an important role in studying new energy sources to protect the environment and combat climate change, including hydrogen storage, fuel cells, solar cells and new types of batteries. It is used in many other R&D, industrial

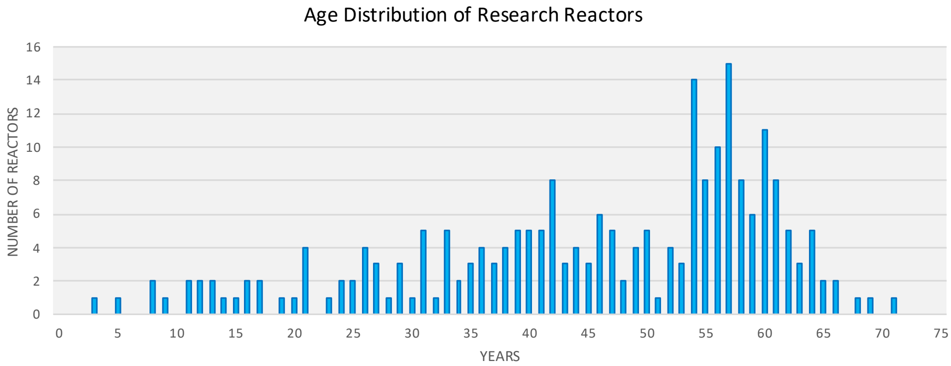


FIG. D-2. Age distribution of operational research reactors, November 2021. (Source: IAEA Research Reactor Database).

and engineering applications. While leading edge R&D made with state-of-the-art neutron scattering instruments is usually done at high performance high flux neutron sources, recent technological developments, in compact accelerator-based neutron sources, especially with the incorporation of advanced in situ sample environments, are opening up new opportunities in neutron scattering at medium flux research reactor and accelerator-based neutron sources.

D.2. Particle Accelerators and Instrumentation

Status

Research reactors have long been the strongest neutron sources available for neutron beam research. However, inherent limitations in steady state reactors, combined with the reduction in use of HEU for civilian purposes, has meant that research reactors have not seen significant performance improvements in neutron flux. Steady improvements in many areas of technology have enabled accelerator-based neutron sources to start to challenge the role of research reactors.

The European Spallation Source (ESS), under construction near Lund, Sweden, supported by 13 participating Member States, is scheduled to come into operation in 2023. The time-integrated flux of the ESS will make it the world's brightest neutron source taking that status from the Laue-Langevin Institute's High-Flux Reactor in Grenoble, France, which it has held for almost half a century. The ESS's neutron producing spallation target is a helium cooled, rotating wheel of tungsten on which a pulsed proton beam of 2 GeV is supplied by a 5 MW (average) proton linear accelerator.

Trends

Accelerator mass spectrometry (AMS) has proven to be not only an ultra-sensitive technique for counting individual atoms but also an accelerator-based method with great potential for analytical applications related to problems of modern society. AMS is presently used in archaeology, biomedicine applications, climate change studies, hydrology, oceanography and many other fields of increasing societal and economic concern. AMS can also be a very powerful tool for nuclear regulatory applications, especially for radioactive waste facilities. As demonstrated in the past five years, AMS has been used to find solutions for major problems related to the decommissioning and long-term safety of nuclear installations, such as site and waste characterization and environmental monitoring of radioactive waste. Radionuclides of interest for site characterization, which AMS is able to quantify, include carbon-14, iodine-129, chlorine-36, technetium-99, krypton-81, beryllium-10 and aluminium-26, whereas for waste characterization the key radionuclides are hydrogen-3, carbon-14, chlorine-36, caesium-135, iodine-129, technetium-99, uranium-236, zirconium-93 and plutonium-240, -241 and -242. Of special interest for regulatory bodies is the characterization of the concrete used in nuclear reactors. This has initiated new AMS feasibility studies for a number of new radioisotopes such as calcium-41.

Recent technological developments of the AMS technique have also expanded the field of its applications, allowing the study of a wide range of cultural and natural heritage objects as well as the detection of forgeries and the illicit trade of products. For example, cutting-edge technological AMS developments have enabled the dating of individual paint layers, pigments, binders and canvas in artworks (Figure D.3).

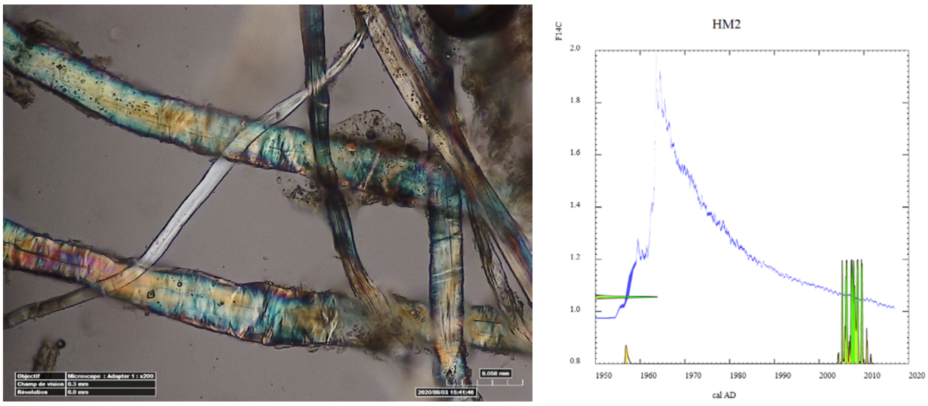


FIG. D-3. Analysis of a post-impressionist painting. Left: Plant-based fabric fibres collected from the paint layer. Right: Age determination using AMS measurement shows the origin of the fabric fibres to be after the alleged artist passed away, thus proving that the painting was a forgery. (Images: Laboratoire de Mesure du Carbone, Université Paris-Saclay, France)

Radiocarbon dating uses the decay of carbon-14 to date objects containing carbon. As a naturally occurring radioactive isotope of carbon, carbon-14 is built into all carbon-bearing material (organic and inorganic) as part of the global carbon cycle. With a half-life of 5700 ± 30 years, detection of carbon-14 is a useful tool for determining the age of a specimen formed over the past 55 000 years.

So far, the most conclusive criterion in the field of counterfeit detection is the scientific proof of material anachronisms, which is based on the comparison of materials present in an artwork with information on their earliest date of discovery or production. Radiocarbon dating is an attractive method, as it delivers absolute ages with a definite time frame for the materials used.

X-ray fluorescence (XRF) spectrometry is a non-destructive, rapid, simultaneous multi-elemental analysis technique for characterization of samples of diverse nature and composition. XRF is a cost-effective choice for many fundamental and applied research projects. Used in combination with X-ray focusing devices, it allows non-destructive determination of elemental distribution in both two and three dimensions. Synchrotron sources provide high intensity X-rays with tuneable selection of energy and spatial focusing for a variety of state-of-the-art techniques for elemental distribution, near surface and ultra-trace analysis

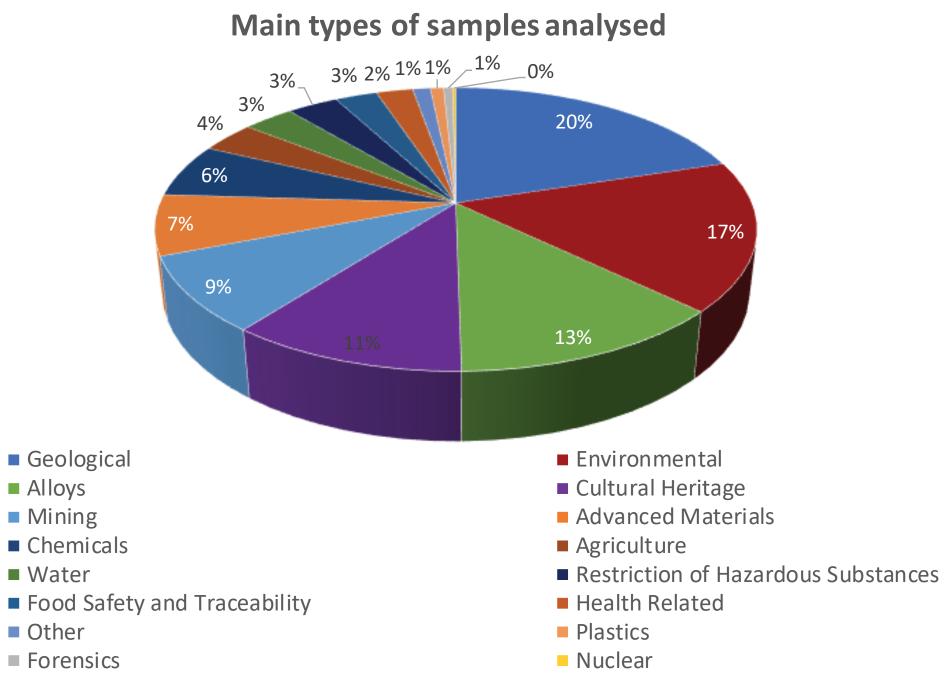


FIG. D-4. Main application fields for a selected XRF facility.

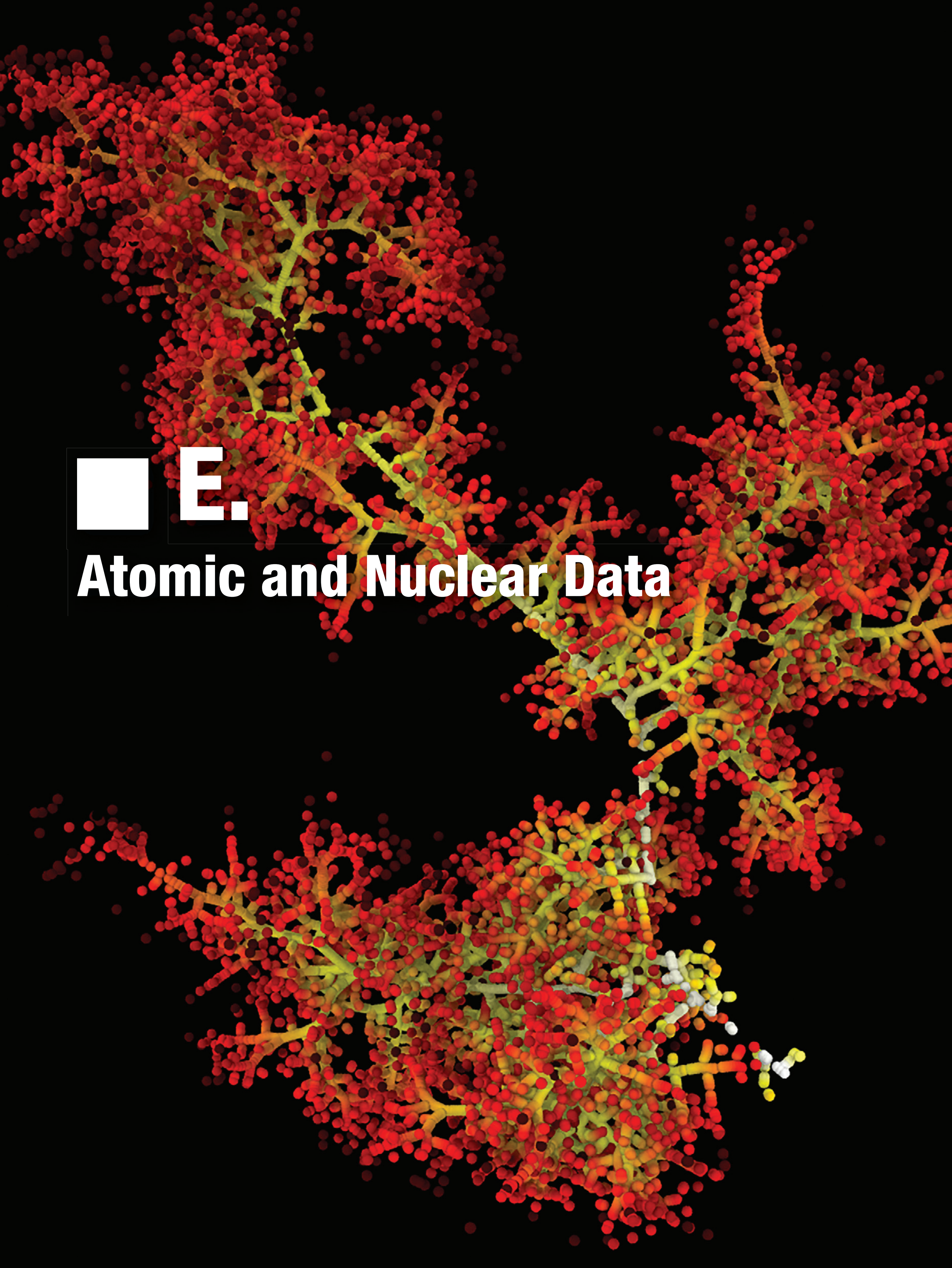
in various fields of materials science such as nanomaterials, biomaterials and energy materials (Figure D.4).

Based on the information available in the Agency's recently developed Interactive Map of XRF Laboratories[11], more than 1200 XRF facilities are currently present in more than 100 countries; however, in many cases their capabilities are yet not well known by the community of end users that might benefit from this powerful analytical technique.

[11] https://nucleus-new.iaea.org/sites/nuclear-instrumentation/Pages/World-Map-XRF-laboratories.aspx

E.

Atomic and Nuclear Data



E. Atomic and Nuclear Data

Status

The development of fusion reactors requires high-quality numerical databases for interactions on the atomic scale. With such data, computational simulation of the design can be performed. Current research focuses on simulations of interaction processes of the plasma and candidate fusion reactor wall material and fundamental atomistic modelling of hydrogen interactions with reactor wall materials (Figure E.1). Experimental research focuses on the fundamental atomic structure of liquid fusion materials and of fusion plasma-liquid metal experiments utilizing linear plasma devices and stellarator-type fusion devices. Theoretical/computational research is performed mostly for the simulation of neutron irradiation effects and hydrogen permeation.

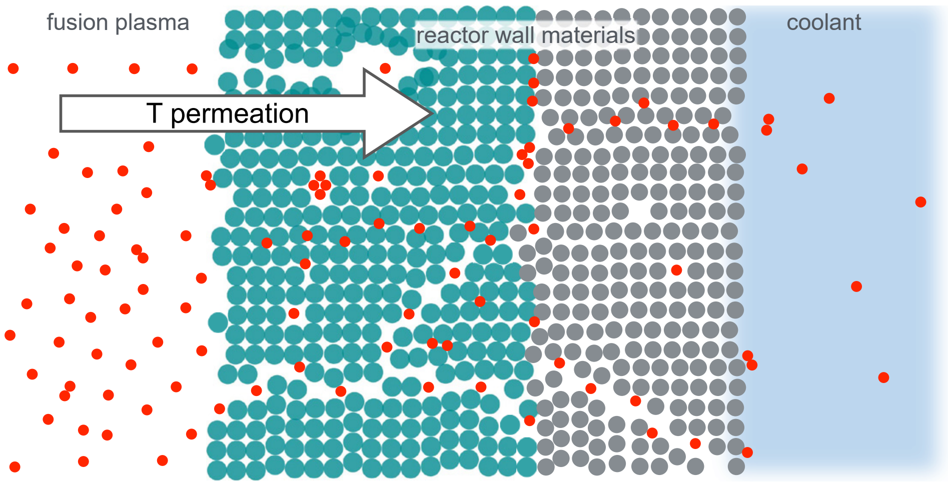


FIG. E-1. Schematic display of the tritium permeation process in a fusion reactor wall.

Trends

The rapid adoption of artificial intelligence/machine learning in various domains is a clear trend that will heavily influence nuclear physics and nuclear data library development. Possible applications range from the prediction of parameters in nuclear model codes like TALYS, trend analysis in experimental data and automated building of the Experimental Nuclear Reaction Data database, to the detection and localization of anomalies in nuclear power plants via modernized and automated data streams. There is a large potential for modern data analysis techniques to improve nuclear data evaluations for nuclear applications.

F.
Environment

F. Environment

Plastic pollution is one of the most pressing global environmental challenges and a direct threat to sustainable development. The NUclear TEChnology for Controlling Plastic Pollution (NUTEC Plastics) initiative, launched in 2021, builds on the Agency's efforts to deal with plastic pollution through recycling using radiation technology and marine monitoring using isotopic tracing techniques.

F.1. Radiation Technologies to Tackle Plastic Pollution

Status

Radiation technologies offer unique characteristics and advantages for reducing plastic and polymer waste by augmenting conventional mechanical plastic recycling and facilitating chemical recycling. The innovative application of gamma and electron beams can enable effective sorting of plastic wastes to feed into recycling streams. This improves the quality and value of the recycled plastics, transforms plastic waste into other higher-value products, and assists advanced or chemical plastic recycling. Such applications also save energy by breaking down waste plastic polymers to be used as chemical feedstocks.

Trends

An application in the Philippines is under development, involving the use of radiation to induce graft polymerization for effective compatibilization for natural fibres with recycled plastic. The radiation-induced polymerization enhances fibre–plastic adhesion which improves the overall thermomechanical properties (Figure F.1). The Philippines is home to a variety of natural fibres such as abaca, banana, pineapple and jute, which are known for their excellent mechanical properties. However, their hydrophilic nature, intrinsic to most lignocellulosic fibres, restricts their application in composites due to poor interfacial adhesion. Radiation-induced graft polymerization overcomes this immiscibility, making them able to mix or attain homogeneity.

Another application, under development in Indonesia, harnesses radiation technology to solve challenges presented by two waste streams. In this approach, plastic waste will be irradiated so it can form stable composites with waste biomass fibres to generate construction materials from plastic and palm waste (Figure F.2). Radiation technologies support the breakdown of biomass, compatibilization of components, and crosslinking in the final product to tailor its properties.

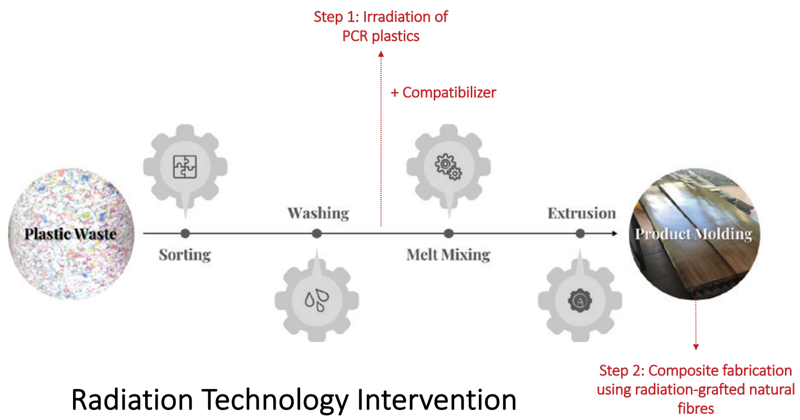


FIG. F-1. Scheme of the proposed composite fabrication using radiation-grafted natural fibres and irradiated post-consumer recycled (PCR) plastics in the Philippines. (Image: Philippine Nuclear Research Institute)

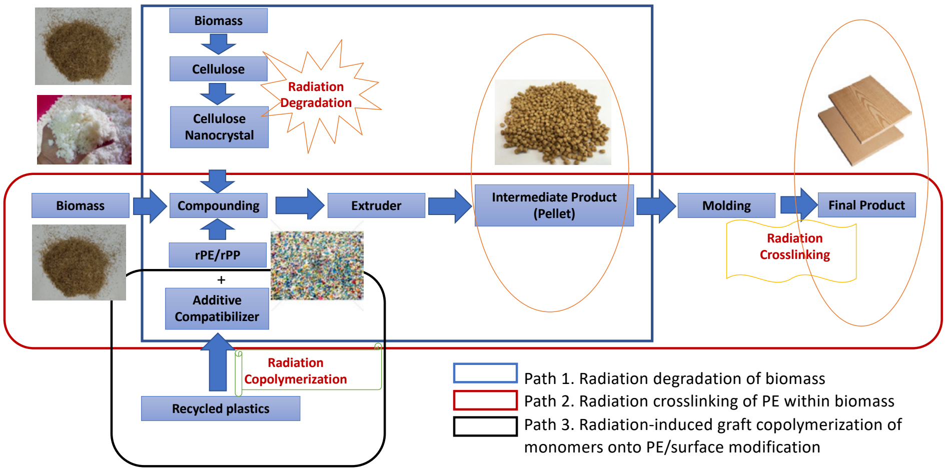


FIG. F-2. Scheme of the proposed production steps for reinforced wood–plastic composite with natural fibres and recycled plastics (recycled polyethylene and recycled polypropylene, rPE/rPP). (Image: National Nuclear Energy Agency of Indonesia)

F.2. Nuclear and Isotopic Techniques to Tackle Plastic Pollution in the Marine Environment

Status

The ocean is the final repository for mismanaged and unrecycled plastics from land-based sources. While the global scientific community has made great progress over the past decade in better understanding plastic pollution in the marine environment and its potential impacts on diverse aquatic organisms, there is still a lack of knowledge regarding the abundance and consequences of microplastics in the ocean. The high profile, visible impacts of macroplastics (Figure F.3) on marine organisms have been well documented, but the potential harm caused by microplastics — particles smaller than five millimetres in diameter — is much less clear. Due to the scale of this problem, plastic pollution has become an issue of global environmental concern and has thus attracted the attention of governments, civil society, scientists and non-governmental organizations.

FIG. F-3. Macroplastics caught with plankton net in the coastal Mediterranean waters.

The global scientific effort on marine plastic pollution has greatly benefited from the use of nuclear technologies. A wide range of nuclear and isotopic techniques has been developed in recent years to determine the composition, size and quantity of plastic debris in the marine environment. These techniques rely on spectroscopic imaging techniques, such as Fourier transform infrared spectroscopy and Raman microscopy, to identify the polymer type and quantify the number of plastic particles larger than ten microns in a natural sample. Complementing these techniques, pyrolysis–gas chromatography–mass spectrometry and thermal desorption–gas chromatography with mass spectrometric detection can simultaneously identify the polymer and analyse both the mass of each type of plastic polymer (from 500 microns down to a thousandth of a micron) and the organic additives associated with the plastic particle in environmentally complex samples.

All these nuclear and isotopic techniques can be applied in the global monitoring of plastics in the marine environment. Together with ocean circulation and dispersion modelling, they contribute to tracing the sources of plastics and their fate in the ocean. The combination of these techniques with measurements of environmental radionuclides (beryllium-7, lead-210, caesium-137 and plutonium-239/240) in sediments and X-ray fluorescence allows scientists to establish the geochronology of sediment cores. This helps scientists to reconstruct the historical trends of marine plastic pollution and better understand the post-sedimentation ageing of microplastics.

Nuclear technologies have also substantively contributed to understanding the transfer of microplastics to marine organisms and their impacts on these organisms. Some microplastic particles are so small that they can be ingested by these organisms and enter their organs, impacting their survival. In addition, microplastics may be a vector for other pollutants. Recent studies have highlighted the usefulness of laboratory-based nuclear techniques in quantifying the movement and biological impacts of microplastics and their associated contaminants, and in detecting stress of marine organisms caused by microplastics. In addition to being used for biodistribution assessments, nuclear imaging techniques such as autoradiography, positron emission tomography (PET) and single photon emission computed tomography can also serve to measure morphological impacts of plastics at both tissue and organism levels.

Trends

To bridge the knowledge gaps in monitoring and characterizing marine plastic pollution, especially regarding smaller sized particles, a suite of research and development efforts are needed. It is imperative that the physical effects of plastic particles themselves are better understood, including their accumulation, translocation and trophic transfer within the marine environment.

To study the accumulation of plastic particles by biota, most studies perform whole body or tissue-specific measurements by digesting tissues and separating particles by filtration, or use tissue sectioning and histological assessment, both followed by visual and/or spectroscopy confirmation. The limitations encountered while using traditional techniques could be resolved by using nuclear methodologies to create radioactive plastic particles, or radioplastics, that can be traced using radiotracing tools. Although radioplastics have recently been used with carbon-14-polymers (beta emitters), future development might utilize gamma emitter radioplastics to assess the retention of microplastics once ingested and their transfer along a food chain. Other nuclear technologies being developed by the Agency and its collaborators involve using stable isotope labelled microplastics, which might offer key advances in understanding the transfer of microplastics and their impact in marine organisms.

Researchers have also begun to consider the fragmentation of plastics at smaller scales, known as nanoplastics. Currently, nanoplastics cannot be quantified in the environment. Although there are analytical methods (fluorimetry and pyrolysis–gas chromatography–mass spectrometry) to study nanoplastics in the laboratory (Figure F.4), these techniques are not necessarily suitable in assessing environmental samples. Nuclear and isotopic techniques have a role to play in addressing and monitoring microplastic fragmentation and the amount of nanoplastics in the future. The challenge of separating and characterizing plastic debris according to size, i.e. microplastics and nanoplastics, is of increasing concern as the nanometric size range might offer more complex and hazardous interactions with biological systems. Flow field-flow fractionation coupled with pyrolysis–gas chromatography–mass spectrometry is a promising methodology to identify the potential impacts of nanoplastics on the environment. Other emerging technologies for quantifying plastic particles in the marine environment include inductively coupled plasma mass spectrometry to obtain information on particle size distribution and mass concentration of nano- and microplastics via carbon-13 detection; and 3D computed tomography, a technique commonly used in engineering research.

Possible risks and hazards of nanoplastics in the environment need to be considered and addressed, and current laboratory-based nuclear techniques are already capable of this. However, the fate and effect of nanoplastics on the environment has thus far only been marginally explored.

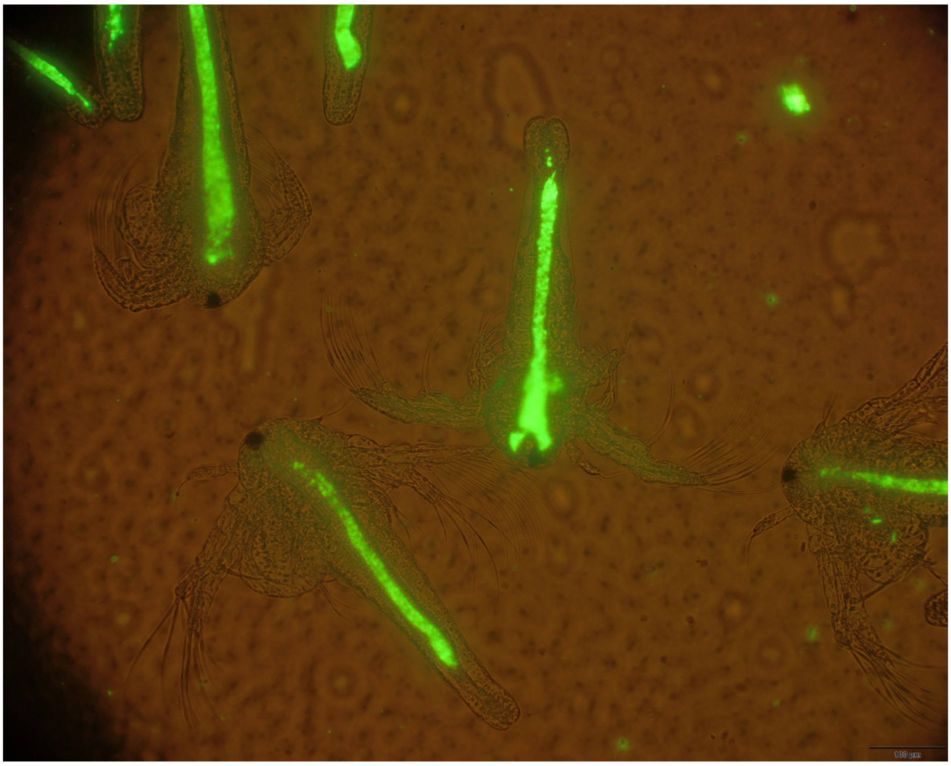


FIG. F-4. Ingestion of nanoplastics by nauplii of the brine shrimp (early life stage of Artemia salinas) made visible through fluorescence.

The expected advances in nuclear and isotopic techniques for monitoring marine pollution and better assessing its impacts on marine organisms must be accompanied by two key developments: capacities around the world to undertake monitoring and assessment activities on marine plastics data must be increased to reach similar levels; and disparities in the validation of monitoring methods must be reduced through comparison, harmonization and standardization to ensure reliable results. Reference materials reflecting the variety of polymer types, broad size range, different shapes and ageing state of microplastic particles found in the ocean are necessary, but at present are non-existent.

Nuclear and isotopic techniques will play a crucial role in combating marine plastic pollution in a sustainable way and in improving informed decision making and science-based management of our ocean.

G.
Food and Agriculture

G.
Food and Agriculture

G.1.
Novel Isotopic Fingerprinting to Assess and Mitigate the Persistence and Transport of Antibiotics and Implications on Antimicrobial Resistance

Status

Antimicrobial substances, such as antibiotics, antivirals, antifungals and antiparasitics, are used to prevent and treat infections in humans, animals and plants. While they save lives, their misuse and overuse are the main drivers for the development of drug-resistant pathogens. The World Health Organization has declared antimicrobial resistance (AMR) as one of the top ten global public health threats, which currently leads to 700 000 deaths every year and is projected to reach ten million deaths per year by 2050.

Antibiotics are widely used in livestock and poultry production for disease control and growth promotion. Between 10% and 90% of administered drugs are not completely absorbed/metabolized by the animal and are excreted in urine and faeces. Either directly as manure (Figure G.1) or indirectly as sewage sludge, these may then be applied as fertilizer or as soil amendments to agricultural land, releasing both the bacteria and the antimicrobial substances and their metabolites into the soil.

AMR occurs when bacteria, viruses, fungi and parasites change over time. They mutate and adapt, and no longer respond to the antimicrobial substances, making infections harder to treat. Antimicrobial resistant organisms are found in people, animals, food, plants and the environment (especially in water and soil). These organisms have an evolutionary advantage and can trigger the development of a microbiome, i.e. a bacterial population, which carries antimicrobial resistant genes. While AMR has been widely studied in human and animal health, its impact on soil and water is still unknown.

FIG. G-1. Soil fertility amendments with manure release both antimicrobials and their metabolites (antimicrobial genes) to the field. (Photo: Chesapeake Bay Program)

The transfer of antimicrobial substances through the environment may lead to antimicrobial residues in plants, animals and food, and the food chain provides many niches where microbial populations abound, and in which AMR can emerge. Thus, both food and the environment play significant roles in the complex pathways of transmission of AMR to humans. Assessing the source and fate of AMR and developing management options will help in reducing the number of associated deaths. This is in line with the One Health approach, which recognizes that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent.

Current conventional chemical methods can be used to assess the spread of antimicrobial substances in the environment and in food, and to study resistance in bacteria, but cannot explain the fate, dynamics and persistence of antimicrobial substances and AMR in agricultural systems. They can measure inventories of antimicrobial concentrations as a snapshot in time but cannot measure unknowns such as metabolites. Antimicrobial substances are continuously introduced into agricultural fields; however, they occur in steady-state concentrations as a result of repeated use. In such a setting it is difficult to detect how these chemicals are degraded over time, and with conventional analysis it is impossible to assess how quickly antimicrobial substances spread in the environment after application, how quickly the input from a fresh application is transformed/metabolized and which metabolites are formed, what contribution the antimicrobial metabolites make to the development of antimicrobial resistant bacterial populations, and what the importance of this current input is relative to previous and subsequent input of the same antimicrobial substance.

Trends

Compound specific stable isotope analysis and probing technologies are powerful tools for the assessment of antimicrobial substances. They can be used to measure the ratios of naturally occurring stable isotopes (e.g. carbon-13 and nitrogen-15) in environmental samples using gas chromatography–isotope ratio mass spectrometry and liquid chromatography–isotope ratio mass spectrometry. They can inform environmental remediation decision makers on the potential contaminant sources and the extent of degradation. Stable isotope probing techniques are used to determine whether biodegradation of a specific contaminant can or does occur at a contaminated site. Stable isotope probing approaches all use isotopically labelled contaminants (carbon-13 with nitrogen-15 and oxygen-18) to detect and quantify biodegradation processes and to characterize the microorganisms responsible for these activities. To understand the dynamic of antimicrobials and AMR through the food chain, an integrated approach using isotope technology and genome sequencing is suggested. This could help investigate the dynamics and excretion of antimicrobials from animals and their fate in the environment (in particular in soil and water), coupled with the evolution and spread of antimicrobial resistant genes.

To apply the above technologies to trace antimicrobials in agricultural systems, the Agency has launched a coordinated research project, entitled “Isotopic Techniques to Assess the Fate of Antimicrobials and Implications for Antimicrobial Resistance in Agricultural Systems”. The compound specific stable isotope analysis technique has been developed to trace the source and fate of pesticides/veterinary antimicrobials on agricultural catchments. The technology is used to monitor the source, dynamics and spread of antibiotics after agricultural application and to assess the potential impact on the environment. The first step is to harmonize the techniques for diagnostics and monitoring of applied manure-labelled synthetic antibiotics. At the moment, insufficient amounts of commercial synthetic labelled antibiotics hinder the field testing of the methodology.

The Agency, through the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, is collaborating with the Technical University of Munich to synthesize labelled sulfamethoxazole and tetracycline (antibiotics commonly used in human and veterinary medicine) through organic synthesis for use in a collaborative field study with partners from Australia, Brazil, China, South Africa and Viet Nam. The aim is to establish analytical protocols/guidelines to trace the flow of antibiotics from human and livestock medications through excretion, manure, contaminated surface and groundwater used for irrigation, and agricultural runoff in the environment. The Agency's Soil and Water Management and Crop Nutrition Laboratory in Seibersdorf will provide hands-on training on implementing isotopic techniques to monitor antimicrobials in the environment. It will also provide guidance on the application of the methodology for developing countries to develop strategies to mitigate the spread of antibiotics in the environment. The Agency's Food and Environmental Protection Laboratory in Seibersdorf will assist by analysing antimicrobials in food using the isotope dilution analysis and compound specific stable isotope analysis.

Recent developments in molecular/biological techniques, such as shotgun metagenomics, can be used to detect and quantify antimicrobial resistant genes. Analyses of other genetic elements or genes, such as the integrase of class integrons, can often provide a good surrogate for the overall presence of anthropogenic pollution, including resistant bacteria in polluted environments. With its genome sequencing platforms, the Agency's Animal Production and Health Laboratory in Seibersdorf will contribute to the project by providing the molecular technologies and hands-on training on laboratory assays to identify antimicrobial resistant strains and tracking AMR-associated genes. The integration of isotopic techniques, such as compound specific stable isotope analysis, and more advanced molecular techniques is expected to trigger a better understanding of the fate and dynamics of antibiotics in applied manure and its implications on antibiotic resistance in the environment.

G.2. Space-induced Genetic Variation, Plant Breeding and Astrobiology to Combat Climate Change

Status

Space is often used for astrobiology research. The specific conditions prevailing in Earth orbit and beyond, in particular the radiation environment and microgravity, have motivated a series of biological experiments since the beginning of space exploration in the late 1950s. Many experiments have focused on the effect of microgravity on plant growth, for instance at the International Space Station (ISS), or in simulated space environments on Earth such as the NASA Space Life Sciences Laboratory.

The focus of these experiments has been on fundamental biology to understand the ability to grow plants productively under the microgravity conditions of space missions. Results have shown that altered gravity has effects on cell proliferation and growth, on gene expression and on epigenetics. Recent experiments explored space-induced genetic variation to see whether new breeds of plants would endure harsh conditions on Earth, such as those caused by climate change. In January 2021, a payload of 320 grapevine cuttings from French researchers was returned to Earth after being held inside the ISS for ten months. In this experiment, researchers are primarily investigating the effect of microgravity in the internal environment of the ISS on the grapevine genome and physiological performance. With a similar research purpose, the plant science company Front Range Biosciences sent tissue cultures of hemp and tobacco to the ISS in 2020.

While a focus on the effects of microgravity on plant biology has driven most astrobiology experiments in the world to date, the radiation environment of outer space has also been used to induce genetic variation in crop seeds for crop improvement through mutation breeding. China has released more than 30 new crop mutant varieties in the past 15 years that were developed through mutagenesis by exposure to space using orbiting satellites, high altitude balloons or by simulated cosmic radiation on Earth. These projects have utilized a combination of the radiation environment and microgravity unique to outer space to induce genetic variation. When in outer space, the seeds were exposed to the external space environment, and not protected from radiation as in the internal environment of the ISS.

Astrobiological experiments investigating the effects of space on plant seeds are still very limited, and they mainly focus on the survivability of seeds along with several microorganisms. The first exposure of microorganisms to space radiation was conducted on sounding rockets in 1965 at 150 km above the Earth, then in the Gemini 9 and 12 missions in 1966 at 300 km, and finally during the return of the Apollo 16 mission from the moon in 1974. Since then, a series of biological experiments has been conducted mainly to prove that life can survive in the extremely harsh conditions of space, primarily focusing on bacteria, algae, lichens and, to a limited extent, plant seeds. These experiments were implemented on specific platforms such as the Long Duration Exposure Facility (LDEF), the European Retrievable Carrier (EURECA), the MIR space station, the research programme Bioinformatics Methodology For Pathway Analysis (BioPAN), the Externally mounted payloads for 1st utilization phase (EXPOSE) on the ISS, the TANPOPO experiment at the Japanese Experiment Module (JEM) of the ISS, the Organism/Organic Exposure to Orbital Stresses (O/OREOS) nanosatellite and its Space Environment Survivability of Live Organisms (SESLO) payload. Recent availability of commercial payloads now facilitates astrobiology experiments at the ISS with internal or external payloads of plant material.

Trends

Scientific information on the mutagenic effects of the space environment at the genomic and physiological levels of crop plants is limited in published literature. Chinese scientists have reported that in wheat seeds sent to space in the recoverable satellite Shijian-8, space radiation and microgravity induced the most frequent mutations. This indicates a synergistic effect between cosmic rays and microgravity, while the single effect of microgravity was much lower than the effect of cosmic rays[12]. Others have revealed pathways and genes involved in mutants with tolerance to salinity generated from spaceflight mutagenesis[13]. Crop seeds have also been sent to the first module of the new Chinese Space Station and to the lunar surface as part of the Chang'e-4 space mission.

[12] Guo, H., et al., Mutagenic effects of different factors in spaceflight environment of Shijian-8 satellite of wheat, Acta Agronomica Sinica Vol. 36 No.5, 2010.

[13] Xiong, H., et al., RNAseq analysis reveals pathways and candidate genes associated with salinity tolerance in a spaceflight-induced wheat mutant, Scientific Reports 7, 2731, 2017.

FIG. G-2. Nanoracks External Platform at the ISS. (Photo: Nanoracks)

There is now increasing interest in understanding the effect of the space environment on producing mutations in plant genomes and in modifying plant physiology, thus improving the ability of plants to withstand adverse growth conditions on Earth such as those induced by climate change. Now payloads of seed or plant material sent to the ISS can be managed by at least two commercial entities that are looking to fill the gap in facilitating or conducting research on the effects of cosmic radiation and microgravity in modifying plant resilience to harsh growth conditions. Rapid advances in the field are foreseen with continuing interest to explore plant biology in space, both for feeding astronauts and for using valuable mutations from space exposure to breed resilient crop varieties.

The Agency, through its Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, will venture into the field of astrobiology and space breeding for the first time in 2022 with an experiment where seeds of two plant species[14] are planned to be placed both within and outside the ISS for a duration of three to seven months for the internal and external payloads, respectively. For the external payload, the Nanoracks External Platform will be used, which is mounted semi-permanently to the JEM Exposed Facility (Figure G.2). The external payload will be installed in the pressurized volume of the ISS before being hosted outside. This will be the world's first systematic exploration to understand and utilize the effects of cosmic radiation and microgravity on induced genetic variation for their potential use in the development of crops that can withstand harsh growing conditions on Earth, such as those imposed by climate change.

[14] *Arabidopsis thaliana*, a small flowering plant commonly used as a model organism in plant biology, and *Sorghum bicolor*, simply known as sorghum, grown for its grain that is used for food for humans, animal feed, and ethanol production.

H.

Human Health

H. Human Health

H.1. Theranostics: A Roadmap to Personalized Cancer Care

Status

Each cancer is made up of different types of cells. For optimal medical care, treatment selection should be based on the identification of cancer subtypes that can be easily characterized by nuclear medicine, allowing for a personalized treatment approach.

Over the past few years, nuclear medicine has undergone impressive growth with the development of PET, especially using fluorine-18 fluorodeoxyglucose, and new approaches in targeted radionuclide therapy, among others. These developments pave the way for personalized cancer management. Radiopharmaceuticals targeting specific biomarkers are powerful tools for the evaluation of disease location and spread, establishment of the prognostic value, evaluation of therapy response, and support for treatment planning or guided biopsies. Moreover, once labelled with beta or alpha emitters, radiopharmaceuticals targeting relevant molecular markers expressed by different solid and haematological tumours can be used for radionuclide targeted therapies.

Modern nuclear medicine plays an essential role in achieving ‘personalized’ or ‘precision’ medicine, allowing the selection of specific treatment appropriate to the individual patient’s condition or predisposition towards a disease. It can therefore address risk assessment, diagnosis, treatment monitoring and radionuclide therapy related to the unique characteristics of the individual to enhance quality of life and public health. This directly contributes to the attainment of the United Nations Sustainable Development Goal 3 on good health and well-being.

Isotope-based theranostics refers to the combination of diagnosis and therapy, enabling medical professionals to focus on the specific needs of each patient. In theranostics, similar molecules embedded with different radioactive isotopes are used for diagnostic or therapeutic purposes. While one radioisotope is used to identify the location and spread of cancer, as well as the specific type of cancer cell, with high precision, another emits radiation to kill cancer cells. Compared to conventional radiation treatments, which more broadly target the disease and its general location, the theranostic approach allows for greater specificity by targeting the tumour with radioactive bullets while sparing the surrounding healthy tissues, increasing both the effectiveness as well as the safety of the treatment (Figure H.1).

The Agency’s support to Member States in establishing facilities and receiving training on theranostics, within the context of safe and appropriate clinical practices, contributes to a transition towards personalized medicine.

Trends

Precision medicine, especially targeted diagnostic imaging, and therapies have made significant progress in recent decades. This has been due in part to the development of new molecules and technologies that led to a rapid growth both in the number of clinical theranostic applications and in their global use.

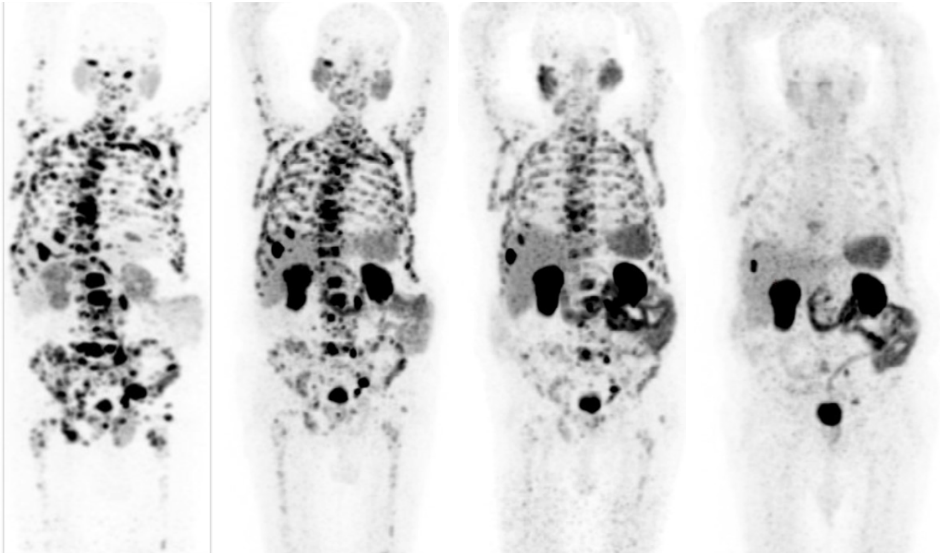


FIG. H-1. Progress of theranostics on an 82-year-old patient with prostate cancer that spread to lymph nodes and bones. Left to right: Condition at beginning of theranostics to near complete remission. (Photos: American University of Beirut Medical Center)

Clinical applications are growing at an accelerated rate. Currently the most prominent applications are for the management of patients with neuroendocrine tumours, lymphoma, prostate, breast, lung and thyroid cancers.

The future of theranostics relies on the development of new molecules designed to target specific tumour cells, thus allowing the treatment of some advanced cancers while reducing the side effects. In this rapidly growing field, there is an emerging need for broader international cooperation and standardization, in training medical and scientific experts and establishing specialized medical infrastructure.

H.2. Advances in Nutrition Science: Helping Countries Tackle the Obesity Epidemic with Data

Status

Nutrition is a vital consideration for all countries in achieving Sustainable Development Goal 3 on good health and well-being. While undernutrition remains at alarmingly high levels, obesity is on the rise. According to the *2021 Global Nutrition Report*[15], adult overweight and obesity are rising in nearly every region and country. 2.2 billion people are overweight, of whom 772 million are affected by obesity. About 6% of children under the age of five were considered overweight in 2020, of which almost half lived in Asia and more than one quarter in Africa. Obesity is a major risk factor for diabetes, cardiovascular diseases, cancer, musculoskeletal disorders and overall mortality. Obesity related illness has reached epidemic proportions globally, with at least 2.8 million people dying each year as a result of being overweight or obese. It is estimated that, globally, obesity-related illness will cost $1.2 trillion yearly by 2025. To tackle the obesity epidemic, the public and national and international policy makers must come together to support effective nutrition interventions, actions and policies. In this context, data on energy expenditure provided by the stable isotope technique of doubly labelled water (DLW) are crucial and will provide policy makers with the evidence to devise more effective nutrition and health policies to combat a growing obesity epidemic worldwide.

[15] https://globalnutritionreport.org/reports/2021-global-nutrition-report/

Total energy expenditure (TEE) as measured by DLW refers to the amount of energy a person expends. It is important for determining energy intake requirements. TEE data inform the development and evaluation of nutrition and physical activity interventions, as well as being the gold standard for validating simple energy intake techniques. The Agency supports the application of the DLW technique as it is the only technique that enables the assessment of TEE under free-living conditions without disruption to everyday activities, making it ideal for use in field settings.

The DLW method uses two stable isotopic tracers, deuterium and oxygen-18, to measure a person's energy expenditure. A person drinks a dose of water containing the two non-radioactive isotopes, and the dose mixes with the water in the body. The isotopes leave the body in urine, sweat and breath. Urine samples are collected before administration of the dose and for seven to 14 days afterwards. Deuterium leaves the body only in body-water, whereas oxygen-18 leaves the body faster in both water and carbon dioxide. The difference in the elimination rates of deuterium and oxygen-18 is a measure of the carbon dioxide production rate, from which energy expenditure can be calculated.

While the method is non-invasive, safe and easily applied in field settings, it can be costly to apply to large populations due to the cost of the isotopes and the analytical equipment required. Studies using DLW have therefore tended to be small; however, pooling data from many studies can provide answers to certain questions that single studies alone cannot, such as how climate change will affect energy requirements in various populations. To facilitate the pooling of global DLW data to answer important questions, in December 2018 the Agency launched a database containing human energy expenditure measurements from the past three decades. As of November 2021, the database includes data on over 7600 subjects from 32 countries, aged between eight days and 95 years. Almost 65% of study participants are female and most of the data are from high income countries.

Trends

The Agency's DLW database can be considered a game changer in the fight against obesity. New findings published in 2021 based on analysis of its data demonstrate how stable isotope techniques are critical for our understanding of human health and in particular of the obesity crisis.

An article published in *Science*[16] dispelled our previous understanding of metabolism (Figure H.2) Using data from the Agency's DLW database, it examined how daily energy expenditure changed through the human life course and showed that metabolism actually has four different phases, from birth to the ninth decade of life. Prominent stages of life, like puberty, pregnancy and menopause, as well as gender and mid-life ageing, do not affect metabolism as much as previously believed. These findings will help scientists better understand important questions about metabolic health and how to help people live healthier lives at every life stage.

Another article published in *Current Biology*[17] focuses on the impact of physical activity on energy balance and shows that increased physical activity does not lead to a TEE as high as was previously thought. This is due to compensation, i.e. more exercising leads to a lower basal metabolism. In addition, people with

[16] Daily energy expenditure through the human life course, Science, Vol. 373, No. 6556, 13 August 2021

[17] Energy compensation and adiposity in humans, Current Biology, Vol. 31, Issue 20, 25 October 2021

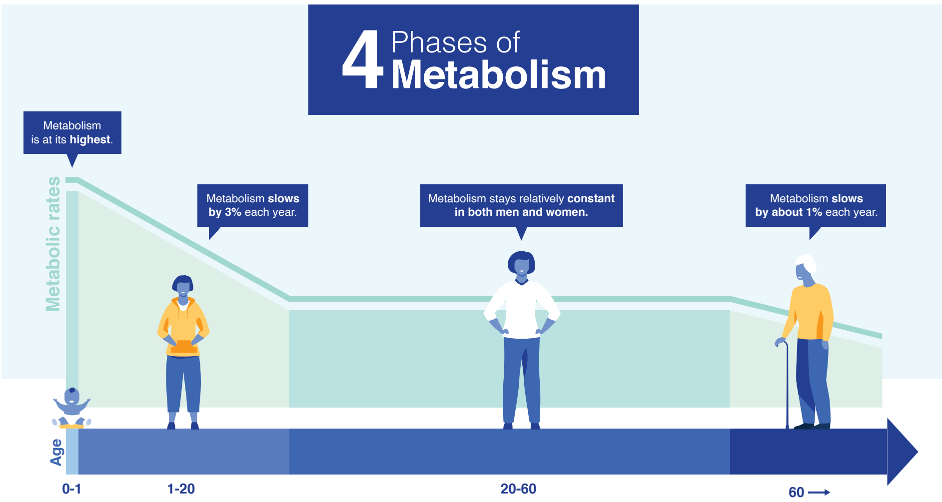


FIG. H-2. The landmark study published in Science dispelled previous understanding of metabolism.

adiposity, or severe obesity, may have more difficulties to burn fat through physical activity than lean people. These new findings also have important implications on public health strategies to fight against overweight and obesity.

More studies and publications are in progress, focusing on issues such as factors influencing water turnover and how much clean water people need to drink each day, the impact of ambient temperature and global warming on energy demands and whether energy expenditure has declined during the obesity epidemic. However, more data are needed from low and middle income countries to strengthen global representation and enable policy makers to have the evidence available to prioritize essential nutrition actions and tackle the obesity epidemic. The Agency will support a new coordinated research project to collect more energy expenditure data from low and middle income countries and ensure the Agency DLW database continues to grow and represent all Member States.

I. Radioisotopes and Radiation Technology

I. Radioisotopes and Radiation Technology

I.1. New Routes for Producing Medical Radioisotopes

Status

Used both for diagnosis and therapy in cancer and other chronic diseases, radioisotopes and radiopharmaceuticals save lives. Ensuring a constant supply of key radioisotopes is essential. Medical radioisotopes, such as molybdenum-99/technetium-99m, fluorine-18, gallium-68, iodine-131 and lutetium-177, are currently produced in research reactors and cyclotrons through nuclear reactions caused by the bombardment of target material with energetic particles, such as neutrons or protons. Following disruptions in the supply of molybdenum-99 during 2007–2010 and in distributions during the COVID-19 pandemic, researchers and producers are developing alternative ways of producing medical radioisotopes. In Canada, cyclotron-produced technetium-99m has been approved and is being commercialized.

Two new production routes for molybdenum-99 using linear accelerators and NPPs open horizons for strengthening and empowering the global supply chain of the world's most used medical radioisotope. Global efforts are also under way to produce medical radioisotopes for innovative and effective therapeutic agents via photodynamic (γ, n) reactions, notably to produce actinium-225 and copper-67.

Accelerator technologies other than cyclotrons can be used for the production of medical radioisotopes (Figure I.1). Targets irradiated at linear accelerators undergo (γ, n) reactions and can produce multiple medical isotopes such as molybdenum-99, actinium-225, copper-67 and scandium-47. An Agency publication under preparation will cover all stages in the process.

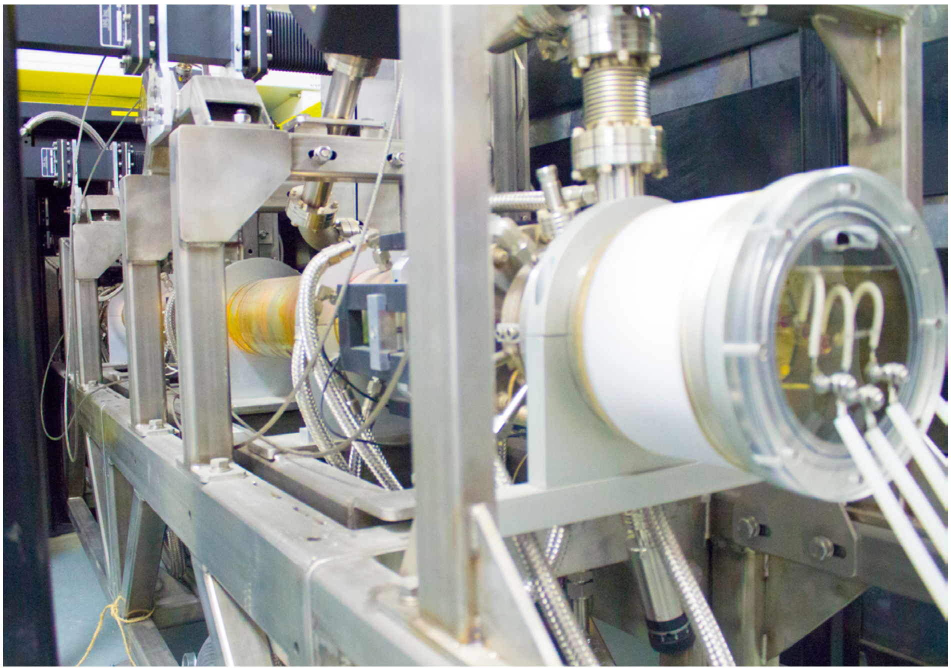


FIG. I-1. A view of a linear accelerator at Canadian Isotope Innovations Corp. (Photo: Canadian Light Source)

Trends

Production of copper-67 and actinium-225 radioisotopes is also possible via such photodynamic reactions. Due to its medium half-life, its beta particle emissions for therapy, and its gamma ray emissions for diagnostic imaging, copper-67 has attracted many researchers and scientists to develop theranostic radiopharmaceuticals, especially those based on monoclonal antibodies. Recent studies based on the photodynamic (γ, n) reaction have successfully produced copper-67 of a high quality for radiopharmaceutical production and application in clinical trials in the USA and Australia.

The nuclide actinium-225 is also of great interest for targeted alpha therapy of cancer patients. Reports[18] on a new photodynamic route for producing actinium-225 indicate that the generated product has fewer impurities and larger quantities than other routes. This is an important result, promising to help meet increasing global demand for actinium-225. A new Agency coordinated research project will focus on the production and quality control of actinium radiopharmaceuticals.

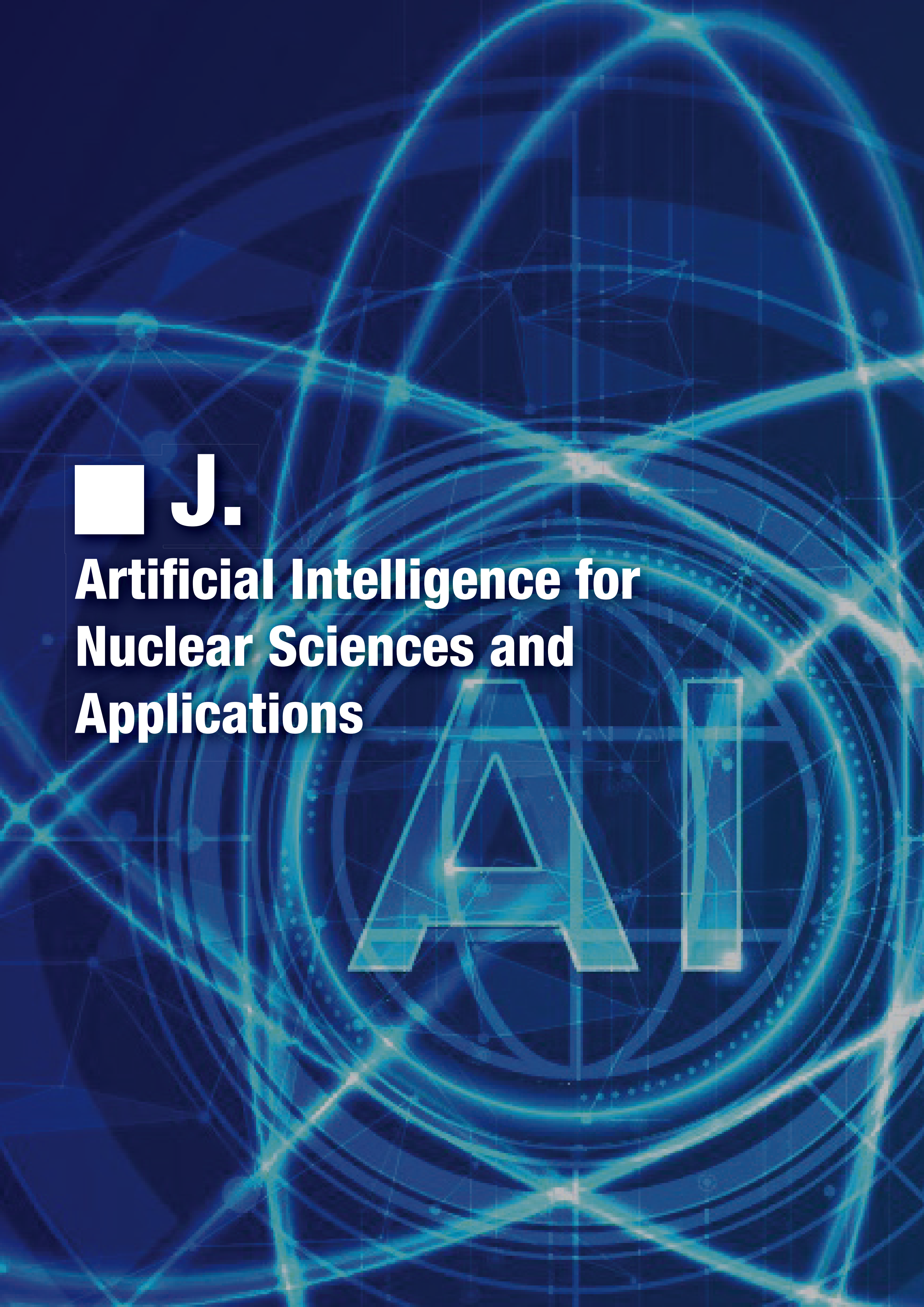
Radioisotope production in reactors is based on neutron capture reactions in a target material. Typically research reactors are used to produce radioisotopes for therapeutic applications in nuclear medicine. Irradiation of targets at NPPs is the usual route for producing some radioisotopes such as cobalt-60, used in industry and brachytherapy. In 2021, a commercial CANDU-type NPP was authorized by the regulator to produce molybdenum-99 (Figure I.2). A similar approach is being explored for producing other important short lived medical radioisotopes at NPPs, including lutetium-177 and holmium-166. This development may also provide new horizons for designers to consider power reactors with radioisotope production capacity.

Wider adoption of these applications, which are currently limited to a few countries, could bring a paradigm shift in medical radioisotope production in future.

FIG. I-2. In 2021, the Canadian Nuclear Safety Commission authorized Darlington NPP to produce the life saving medical radioisotope molybdenum-99.
(Photo: Ontario Power Generation)

[18] Actinium-225 production with an electron accelerator, Journal of Applied Physics 129, 104901 (2021)

■ J.
Artificial Intelligence for Nuclear Sciences and Applications



J. Artificial Intelligence for Nuclear Sciences and Applications

Status

Artificial intelligence (AI) refers to a collection of technologies that combine numerical data, process algorithms, and continuously increase computing power to develop systems that can approach complex problems in ways similar to human logic and reasoning. AI technologies can analyse large amounts of data to learn and assess how to complete a particular task, a technique called machine learning.

Artificial intelligence is advancing exponentially and can already sort and interpret massive amounts of data from various sources to carry out a wide range of tasks and help tackle many of the world's most urgent challenges. It has enormous potential to accelerate technological development in many nuclear fields from nuclear medicine to water resources management to nuclear science and industry. For example, AI's ability to recognize data patterns and analyse high resolution images from satellites, drones, or medical scans can improve responses to humanitarian emergencies, detect global hydro-climatic changes signalling drought or floods, monitor and optimize agricultural productivity, track animal and marine migrations, and help medical professionals identify and treat cancers and other diseases.

Combining isotope science with AI provides an interpretable framework to extract new information from small isotopic variations, offering great potential in a multitude of fields including isotope hydrology, ecology, forensics and food security. Experts already apply AI-based approaches to quickly analyse huge amounts of water-related isotopic data stored in global networks, such as the Global Network of Isotopes in Precipitation maintained by the Agency and the World Meteorological Organization. Effective and efficient analysis of these data facilitated with AI helps scientists understand climate change and the impact of climate change and population growth on water availability worldwide.

In fusion and nuclear science research, machine learning enables optimization of experimental planning and real time control solutions necessary for sustained, safe, and efficient facility operation, by maximizing the amount and applicability of information extracted from experimental and simulation data.

Artificial intelligence can also contribute to combating cancer while helping keep associated costs down. Artificial intelligence-based approaches are applied to support diagnosis and treatment of cancer through improved image interpretation and precise tumour contouring, enabling the development of accurate treatment plans as well as adaptive radiotherapy — a radiation therapy process that adapts to internal anatomical variants of the individual patient. Machine learning plays an increasingly important role in medical imaging for the prediction of individual disease course and treatment response. Artificial intelligence will also play an important role in the Agency's Zoonotic Disease Integrated Action (ZODIAC) initiative to help experts predict, identify, assess, and contain future zoonotic disease outbreaks.

Trends

Enhanced use of AI in nuclear sciences and applications requires a combined effort across disciplines, including information curation and sharing, and transparent development activities to coordinate and support collaboration among researchers from a wide spectrum of fields.

Artificial intelligence technologies require strong international partnerships and cross-cutting cooperation for the development of guidance in regulation, ethical issues, education and training as well as for sharing experiences, knowledge, and good practices. These include the need for AI applications to be inclusive, just and equitable to benefit the entire society. This is of particular importance for AI applied to nuclear technologies targeting equitable sustainable development for present and future generations.

Recognizing the benefits and opportunities AI brings, as well as its challenges, including concerns about transparency, trust, security and ethics, the Agency is seeking open dialogue and collaboration to promote the application of AI to nuclear science and technologies, in order to better support its Member States in the peaceful use of nuclear technologies.

The AI for Good movement, organized by the International Telecommunication Union (ITU) and 38 organizations in the United Nations family, including the Agency, is an all year digital platform aimed at identifying applications of AI to accelerate the achievement of the Sustainable Development Goals (Figure J.1). The Agency's two webinars held in November 2021 within AI for Good, as well as a pioneering Technical Meeting on Artificial Intelligence for Nuclear Technology and Applications held in October 2021, provided an international, cross-cutting forum to discuss, identify, and foster nuclear science, technology, and applications.

These events highlighted how database development and data accessibility can be real enablers for AI applications. They emphasized the importance of establishing, where practical, centralized and federated repositories gathering well-curated data to allow AI and machine learning applications; promoting federated learning (moving models rather than data) for training the model from one database to another database and building literature libraries to collect references for AI and machine learning in nuclear technologies and applications.

The Agency seeks to establish the foundations for continued AI innovation in nuclear science and applications by establishing an 'AI for Atoms' knowledge-sharing platform, as well as supporting regulation and training, and promoting ethical guidance.

FIG. J-1. The AI for Good platform brings together 38 organizations in the United Nations family. (Photo: ITU)

■ Annex

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

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2021		Total Operating Experience through 2021	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	3	1641	1	25	10.2	7.2	94	2
ARMENIA	1	4488			1.9	25.3	47	8
BANGLADESH			2	2160	NA	NA		
BELARUS	1	1110	1	1110	5.4	14.1	1	2
BELGIUM	7	5942			48.0	50.8	317	7
BRAZIL	2	1884	1	1340	13.9	2.4	61	3
BULGARIA	2	2006			15.8	34.6	171	3
CANADA	19	13624			86.8	14.3	807	6
CHINA	53	50034	16	15967	383.2	5.0	470	0
CZECH REPUBLIC	6	3934			29.0	36.6	182	10
FINLAND	4	2794	1	1600	22.6	32.8	171	4
FRANCE	56	61370	1	1630	363.4	69.0	2393	0
GERMANY	3	4055			65.4	11.9	830	11
HUNGARY	4	1916			15.1	46.8	146	2
INDIA	22	6795	8	6028	39.8	3.2	554	9
IRAN, ISLAMIC REPUBLIC OF	1	915	1	974	3.2	1.0	10	4
JAPAN	33	31679	2	2653	61.3	7.2	1965	6
KOREA, REPUBLIC OF	24	23091	4	5360	150.5	28.0	620	2
MEXICO	2	1552			11.6	5.3	59	11
NETHERLANDS	1	482			3.6	3.1	77	0
PAKISTAN	5	2242	1	1014	15.8	10.6	92	11
ROMANIA	2	1300			10.4	18.5	39	11
RUSSIAN FEDERATION	37	27727	4	3759	208.4	20.0	1410	7
SLOVAKIA	4	1868	2	880	14.6	52.3	180	7
SLOVENIA	1	688			5.4	36.9	40	3
SOUTH AFRICA	2	1854			12.2	6.0	74	3
SPAIN	7	7121			54.2	20.8	357	1
SWEDEN	6	6882			51.4	30.8	480	0
SWITZERLAND	4	2960			18.6	28.8	232	11
TÜRKİYE			3	3342	NA	NA	NA	NA
UKRAINE	15	13107	2	2070	81.1	55.0	548	6
UNITED ARAB EMIRATES	2	2762	2	2690	10.1	1.3	1	9
UNITED KINGDOM	12	7343	2	3260	41.8	14.8	1648	6
UNITED STATES OF AMERICA	93	95523	2	2234	771.6	19.6	4694	4
Total [b,c]:	**437**	**389508**	**56**	**58096**	**2653.1**	**NA**	**19170**	**9**

Note: NA — Not applicable.

[a] Source: Agency's Power Reactor Information System (PRIS) (www.iaea.org/pris) as of 31 May 2022.

[b] The total figures include the following data from Taiwan, China: 3 units, 2 859 MW(e) in operation and 26.8 TWh of electricity supplied, accounting for 10.8% of 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 (236 years, 8 months).

Table D-1. Common applications of research reactors around the world[19]

Type of application [a]	Number of research reactors involved [b]	Number of Member States hosting such facilities
Teaching/training	162	50
Neutron activation analysis	117	49
Radioisotope production	83	41
Neutron radiography	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	11
Nuclear data measurement	14	7
Other [c]	118	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 235 research reactors considered (220 in operation, 15 temporarily shut down, as of December 2021).

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

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[19] Status as per December 2021

Abbreviations and Acronyms

AI	artificial intelligence
AMR	antimicrobial resistance
AMS	accelerator mass spectrometry
ASN	Nuclear Safety Authority (France)
ATF	advanced technology fuel
BioPAN	Bioinformatics Methodology for Pathway Analysis
COP26	26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (2021)
COP27	27th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (2022)
COVID-19	coronavirus disease 2019
DGR	deep geological repository
DLW	doubly labelled water
DSRS	disused sealed radioactive source
DTT	Divertor Tokamak Test facility
EDF	Électricité de France
ESS	European Spallation Source
EXPOSE	Externally mounted payloads for 1st utilization phase
EURECA	European Retrievable Carrier
FAO	Food and Agriculture Organization of the United Nations
FEPC	Federation of Electric Power Companies of Japan
GURC	generic user requirements and criteria
GW(e)	gigawatt (electrical)
GW·h	gigawatt hours
HALEU	high assay low enriched uranium
HEU	high enriched uranium
HTR	high temperature reactor
HTTR	High Temperature Engineering Test Reactor
INIR	Integrated Nuclear Infrastructure Review
iPWR	integral PWR
ISF	interim storage facility
ISS	International Space Station
ITU	International Telecommunication Union
IWP	Integrated Work Plan
JMTR	Japan Materials Testing Reactor
LDEF	Long Duration Exposure Facility
JEM	Japanese Experiment Module
LEU	low enriched uranium
LTO	long term operation
LWR	light water reactor

MOX fuel	mixed oxide fuel
MW(e)	megawatt (electrical)
MW(th)	megawatt (thermal)
NDA	Nuclear Decommissioning Authority
NDC	nationally determined contribution
NNL	National Nuclear Laboratory (United Kingdom)
NORM	naturally occurring radioactive material
NPM	NuScale Power Module
NPP	nuclear power plant
NPPA	Nuclear Power Plants Authority (Egypt)
NRC	Nuclear Regulatory Commission (USA)
NUTEC Plastics	Nuclear Technology for Controlling Plastic Pollution
O/OREOS	Organism/Organic Exposure to Orbital Stresses
PCR	post-consumer recycled
PET	positron emission tomography
PHWR	pressurized heavy water reactor
PWR	pressurized water reactor
R&D	research & development
rPE/rPP	recycled polyethylene and recycled polypropylene
SCWR	supercritical water cooled reactor
SDA	standard design approval
SESLO	Space Environment Survivability of Live Organisms
SFR	sodium cooled fast reactor
SMART	system-integrated modular advanced reactor
SMR	small and medium sized or modular reactor
SNF	spent nuclear fuel
STEP	Spherical Tokamak for Energy Production
TEE	total energy expenditure
t HM	tonnes of heavy metal
UKAEA	United Kingdom Atomic Energy Authority
UNFCCC	United Nations Framework Convention on Climate Change
URF	underground research facility
WCR	water cooled reactor
XRF	X-ray fluorescence
ZODIAC	Zoonotic Disease Integrated Action

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