Nuclear Technology Review 2021

Report by the Director General

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

GC(65)/INF/2

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Contents

Foreword

- In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* each year.
- The *Nuclear Technology Review 2021* covers the following select areas: nuclear power, nuclear fuel cycle, decommissioning, environmental remediation and radioactive waste management, research reactors and particle accelerators, nuclear techniques in food and agriculture, human health, radioisotopes and radiation technologies, and environment.
- The draft version was submitted to the March 2021 session of the Board of Governors in document GOV/2021/2. This final version was prepared in light of the discussions held during the Board of Governors and also of the comments received by Member States.

Executive Summary

The Agency's 2020 projections remained largely in line with the previous year's projections. In the high case, global nuclear electricity generating capacity was projected to increase by 82% to 715 gigawatts (electrical) (GW(e)) by 2050, corresponding to 11% of global electricity generation, versus around 10% in 2019. The low case projected a decrease of 7% to 363 GW(e), representing a 6% share of global electricity generation.

At the end of 2020, the world's total nuclear power capacity was 392.6 GW(e), generated by 442 operational nuclear power reactors in 32 countries. The nuclear sector adapted to national guidelines with regard to the coronavirus disease (COVID-19) pandemic by taking effective measures. At the outset of the pandemic in early 2020, the Agency established the COVID-19 Nuclear Power Plant Operating Experience Network to help share information on measures taken to mitigate the pandemic and its impact on the operation of nuclear power plants (NPPs). None of the 32 countries with operating nuclear power plants reported any impact on safe and reliable NPP operation due to the pandemic.

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. Nuclear power supplied 2553.2 terawatt-hours of electricity in 2020, accounting for nearly a third of the world's low carbon electricity production. It is widely recognized that, to address the challenges of a clean energy transition, nuclear power will have to play a significant role.

Some 5.5 GW(e) of new nuclear capacity was connected to the grid, from five new pressurized water reactors in Belarus, China, the Russian Federation and the United Arab Emirates. The start-up of Belarusian-1 in Belarus and of Barakah-1 in the UAE marked the first nuclear electricity generation in these two countries.

Global activities on the technology development of small, medium sized or modular reactors (SMRs) for near term deployment made tangible progress. The world's first advanced SMR and only floating NPP, Akademik Lomonosov, started commercial operation in the Russian Federation. There were more than 70 SMR designs of major technology lines under development for different applications worldwide.

Long term operation and ageing management programmes were under way for an increasing number of nuclear power reactors globally, especially in North America and Europe. In the United States of America, the operational licences for Peach Bottom-2 and -3 nuclear power units were renewed, extending safe and secure operation from 60 to 80 years.

A total of 27 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, adding an estimated 26 GW(e) of global generating capacity.

The fusion community celebrated the start of ITER assembly and integration after more than ten years of complex construction phases. Once in operation, ITER will provide much of the scientific and technological basis for the development and design of future fusion reactors for energy production.

As a result of the global COVID-19 pandemic, several major uranium producers suspended operations or significantly reduced production. Overall, primary uranium supply was lower in 2020, putting pressure on secondary uranium supplies to fill the demand for uranium as nuclear fuel.

During the COVID-19 pandemic, research reactors producing medical radioisotopes for global supply were declared as providing essential services to minimize the effect of pandemic related restrictions.

While there is considerable and growing interest in SMRs, advanced large water cooled reactors were expected to make up the bulk of new capacity additions over the next three decades. To achieve the Agency’s high case projection, a yearly grid connection rate of 16 GW(e) or more would be required up to 2050. However, a number of challenges would need to be addressed to facilitate new build projects, including cost reductions and enhanced standardization to improve competitiveness, and access to financing on a level playing field with other low carbon energy sources.

The use of nuclear energy beyond electricity production is gaining more traction in the nuclear energy sector due to the increasing share of variable renewables connected to the grid. A total of 64 operating nuclear power reactors were used to generate 3396.4 gigawatt-hours of electrical equivalent heat for non-electric applications: 56 reactors supported district heating and industrial process heat applications and 8 supported desalination. In addition to its role in decarbonizing end-use sectors, such as transport, industry or the residential sector, nuclear cogeneration was increasingly seen as an opportunity to build an economic case against the early retirement of some non-profitable NPPs. Interest in nuclear hydrogen production using low temperature water cooled reactors was expected to continue towards the commercial stage.

Major advancements were observed with regard to deep geological disposal facilities needed for high level waste and spent fuel declared as waste. The Finnish Radiation and Nuclear Safety Authority announced that Finland intends to begin the final disposal of used nuclear fuel in the mid-2020s. In Sweden, the municipal council of Östhammar voted in favour of a planned repository for spent nuclear fuel at Forsmark.

While in previous decades deferred dismantling was the dominant decommissioning strategy adopted by facility owners, an immediate dismantling approach has been gaining favour. Timeframes for beginning final dismantling of retired plants were increasingly brought forward, driven by a desire to reduce uncertainties over decommissioning costs.

Global interest in research reactors continued to grow. Many countries took advantage of opportunities to access existing research reactors, including through the Agency’s regional research reactor schools for capacity building and through the IAEA-designated International Centre based on Research Reactor (ICERR) scheme. In 2020, the Institute for Nuclear Research, Pitesti in Romania was newly designated, while the French Alternative Energies and Atomic Energy Commission was re-designated as ICERR for a period of five years.

During food production, chemicals such as veterinary drugs and pesticides are used to prevent and treat animal and plant pests and diseases. Remnants of these chemicals in food may present public health and trade concerns and are, therefore, regulated by prescribing the highest concentrations of residues allowed in/on food. Radiolabelled compounds play a crucial role, as they allow for the tracing and studying of all chemical residues in various tissues. Those studies are critical for the establishment of acceptable standards. With increasing production of new drugs and chemicals the demand to regulate them using innovative, cost-effective analytical techniques has been rising.

Microdosimetry is the subfield of radiation physics dealing with the systematic study of the spatial distribution of the absorbed energy in microscopic structures within irradiated matter. Although it originated more than 60 years ago, microdosimetry continues to attract scientific interest in radiation medicine, radiation protection, radiation biology and other fields such as space research. In the field of radiation medicine, microdosimetry is particularly relevant for ion beam therapy, an advanced technique that uses proton and carbon ion beams to cure a number of tumours, minimizing the damage to healthy tissue.

Infectious diseases are a threat to human populations. Scientific disciplines are focusing their efforts to better understand such diseases with advanced technologies using radiopharmaceuticals. Novel radiopharmaceuticals prepared with microorganism-specific monoclonal antibodies are at a stage where non-invasive visualization of the cellular and biochemical processes is becoming possible, improving the diagnosis and potential therapeutic approaches for infectious diseases.

The rapid rise in atmospheric greenhouse gases, such as carbon dioxide, methane and nitrous oxide, since the late 19th century, has contributed to global warming. Ocean and vegetated coastal ecosystems have notable organic carbon sequestration potential, as they can capture and store carbon dioxide away from the atmosphere, thereby reducing the rate of global warming. The organic carbon captured and stored by the ocean is known as blue carbon. Nuclear and derived techniques are instrumental in the assessment of the role of carbonate and macroalgae in the blue carbon cycle, the determination of carbon provenance, understanding factors that influence sequestration in blue carbon ecosystems and their corresponding budgets, and management actions that promote blue carbon strategies.

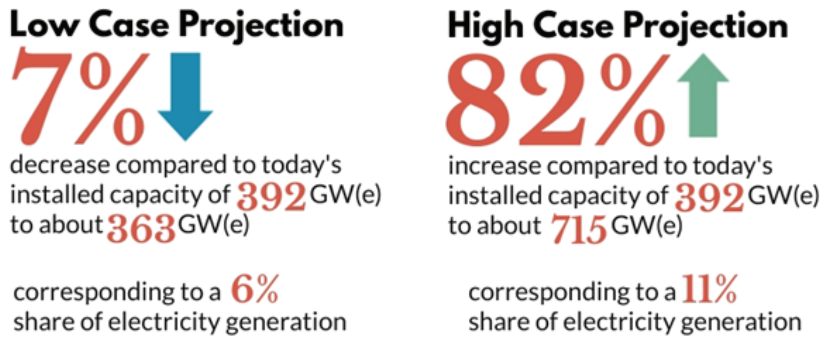
A.
Nuclear Power

A. Nuclear Power

A.1. Nuclear Power Projections

Status

The Agency's 2020 projections[1] remained largely in line with the previous year's projections. In the low case estimate, global nuclear electricity generating capacity will decrease by 7% to 363 GW(e)[2] by 2050, representing a 6% share of global electricity generation versus around 10% in 2019. The high case projects an increase of 82% to 715 GW(e), corresponding to 11% of global electricity generation.



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 new capacity, of the order of 500 GW(e) over three decades, will be required. This will require the connection of more than 16 GW(e) of new capacity a year up to 2050, an almost threefold increase from the average connection rate between 2010 and 2019. While ambitious, that rate would still be only half of the record rate of over 30 GW(e) of annual connections achieved during the mid 1980s.

Trends

There is considerable and growing interest in the small and medium sized or modular reactors (SMRs) particularly in remote locations or in countries with smaller grids. However, advanced large water cooled reactors are expected to make up the bulk of new capacity additions over the next three decades to quickly add capacity for low carbon energy in the fight against climate change.

The nuclear sector faces a number of challenges in this regard including cost reductions and enhanced standardization to improve competitiveness, and access to financing on a level playing field with other low carbon energy sources.

Strong policy support recognizing the contribution of nuclear power to resilient and reliable low carbon power systems[3] will be needed. 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.

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Reference Data Series No. 1, IAEA, Vienna (2020).

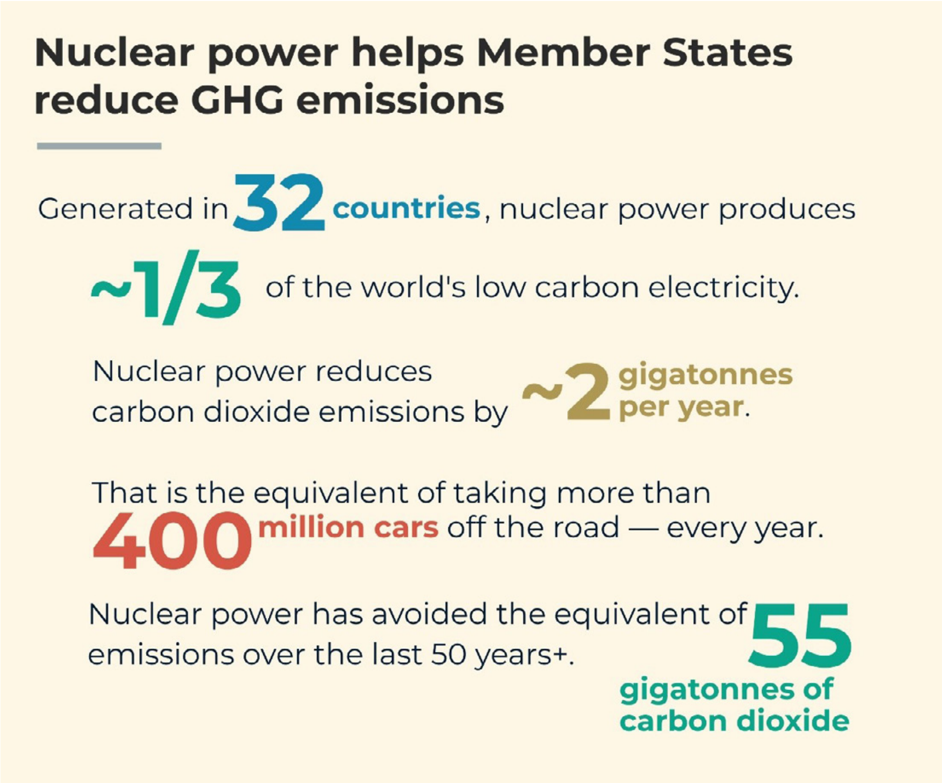
[2] GW(e), or gigawatt (electrical), equals one thousand million watts of electrical power.

[3] About two gigatonnes of carbon dioxide is avoided each year owing to nuclear power.

A.2. Operating Power Plants

Status

At the end of 2020, the world's total nuclear power capacity was 392.6 GW(e)[3], generated by 442 operational nuclear power reactors in 32 countries (Table A-1 in the Annex). Countries demonstrated adaptability to the coronavirus disease (COVID-19) pandemic by taking effective measures, reflecting strong organizational culture. At the outset of the pandemic in early 2020, the Agency established the COVID-19 Nuclear Power Plant Operating Experience Network (COVID-19 NPP OPEX) to share information on measures taken to mitigate the pandemic and its impact on the operation of nuclear power plants (NPPs). 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 (GHG) emissions worldwide, while fulfilling the world's increasing energy demands and supporting sustainable development and post-COVID-19 pandemic recovery. In 2020, nuclear power supplied 2553.2 terawatt-hours of GHG emission-free electricity, accounting for about 10% of total global electricity generation and nearly a third of the world's low carbon electricity production.

Some 5.5 GW(e) of new nuclear capacity was connected to the grid, from five new pressurized water reactors (PWRs): 1110 MW(e) at Belarusian 1 in Belarus, 1000 MW(e) at Tianwan-5 and 1000 MW(e) at Fuqing 5 in China, 1066 MW(e) at Leningrad 2-2 in the Russian Federation and 1345 MW(e) at Barakah-1 in the United Arab Emirates. The start-up of Belarusian-1 in Belarus and of Barakah-1 in the United Arab Emirates marked the first instances of nuclear electricity generation in these two countries.

[4] All data on nuclear power reactors as reported to the IAEA Power Reactor Information System (PRIS) as of 1 June 2021.

2020 Connections to the Grid

Barakah-1
1345 MW(e)

Belarusian-1
1110 MW(e)

Leningrad 2-2
1066 MW(e)

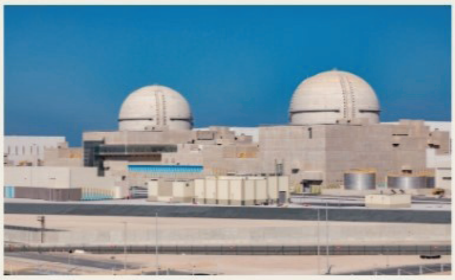
Fuqing-5
1000 MW(e)

Tianwan-5
1000 MW(e)

Belarusian-1

Type	Model
PWR	VVER V-491
Net Capacity	**Construction Start**
1110 MW(e)	8 Nov 2013
First Criticality	**First Grid Connection**
11 Oct 2020	3 Nov 2020
INIR 1+2 Missions	**INIR 3 Mission**
2012	2020

Barakah-1



Type	Model
PWR	APR-1400
Net Capacity	**Construction Start**
1345 MW(e)	19 Jul 2012
First Criticality	**First Grid Connection**
31 Jul 2020	19 Aug 2020
INIR 2 Mission	**INIR 3 Mission**
2011	2018

The world's first advanced SMR and only floating NPP, Akademik Lomonosov, started commercial operation in 2020. It is located just off the Arctic coast in the Russian Federation and features two 35 megawatt (electrical) (MW(e)) KLT-40S SMR units.

Some 89.5% of operational nuclear power capacity comprised light water moderated and cooled reactor types; 6% were heavy water moderated and cooled reactor types; 2% were light water cooled and graphite moderated reactor types; and the remaining 2% were gas cooled reactor types. The remaining 0.5% were three liquid metal cooled fast reactors.

LTO and ageing management programmes were under way for an increasing number of nuclear power reactors globally, especially in North America and Europe. In the United States of America, the operational licences for Peach Bottom-2 and -3 nuclear power units were renewed, extending safe and secure operation from 60 to 80 years.

Refurbishments and major upgrade projects continued despite the challenges posed by the COVID-19 pandemic. For example, the refurbishment of Darlington-2 in Canada and the modernization of the control and emergency systems at Doel-1 and -2 in Belgium were completed during this period. In the United States of America, Grand Gulf-1 returned to the grid after a scheduled refuelling and maintenance outage, including equipment upgrades and modernization of the plant's turbine control system.

During the year, 5.2 GW(e) of nuclear capacity was retired, with the permanent shutdown of six nuclear power reactors: Fessenheim-1 (an 880 MW(e) PWR) and Fessenheim-2 (an 880 MW(e) PWR) in France, Leningrad 2 (a 925 MW(e) light water graphite reactor in the Russian Federation, and Duane Arnold (a 601 MW(e) boiling water reactor) and Indian Point-2 (a 998 MW(e) PWR) in the United States of America. Ringals 1 (an 881 MW(e) BWR in Sweden was shut down on the last day of 2020, after more than 46 years of service.

World's Cumulative Nuclear Reactor Operating Experience

18 772 reactor years

with **479.9** GW(e) total capacity

634 reactors

35 countries ever having operated an NPP

Trends

Overall, nuclear power capacity in the past decade has shown a gradual growth trend, including some23.7 GW(e) of new capacity added by new reactors or upgrades to existing reactors. Nuclear power generation has demonstrated continuous growth, expanding by more than 6% since 2011.

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 for building 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. This is particularly the case in the United States of America, where around ten reactors were shut down for economic reasons in the past decade, being unable to compete with low-cost shale gas or subsidized renewables. Some parts of the country have introduced market mechanisms such as zero-emission credits to value the contribution of nuclear power to the decarbonization of the power mix, and to keep existing plants open. In other parts of the world, the appropriate policy decisions may be key to allowing LTO of existing reactors.

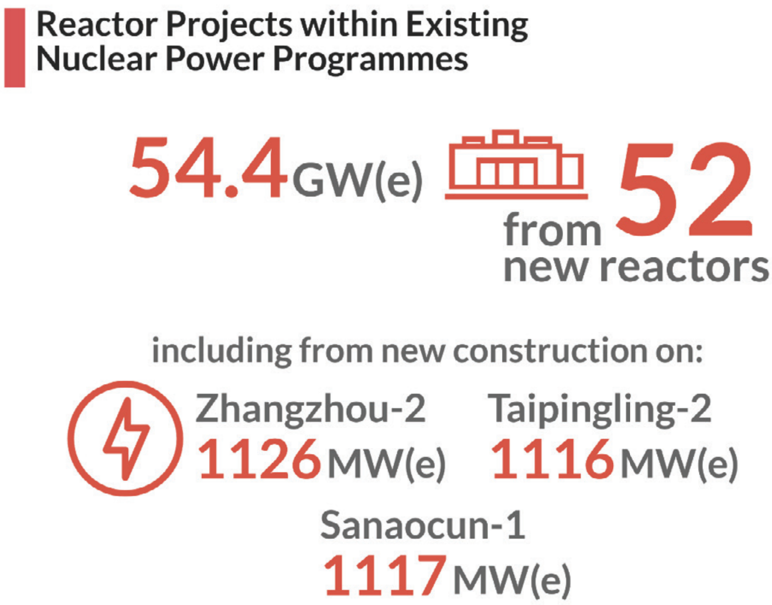
In addition, some uncertainties remained linked to the nuclear power industry supply chain. Closure of industries deemed non-essential in the short term will have a yet unknown impact on medium- to long-term supply continuity at nuclear reactors worldwide. The existing supply chains were facing challenges 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

Installed nuclear power capacity under construction has remained largely unchanged in recent years, with slower new construction growth in 2020. The Asia region continued to experience a steady expansion in nuclear power capacity, with a total of 58.5 GW(e) operational capacity from 64 reactors connected to the grid since 2005.

Of the 32 countries that use nuclear power, 19 had projects in place to expand their nuclear capacity, including Belarus and the United Arab Emirates that have connected to the grid their first nuclear power reactors in 2020. These projects comprised a total capacity of 54.4 GW(e) from 52 new reactors.

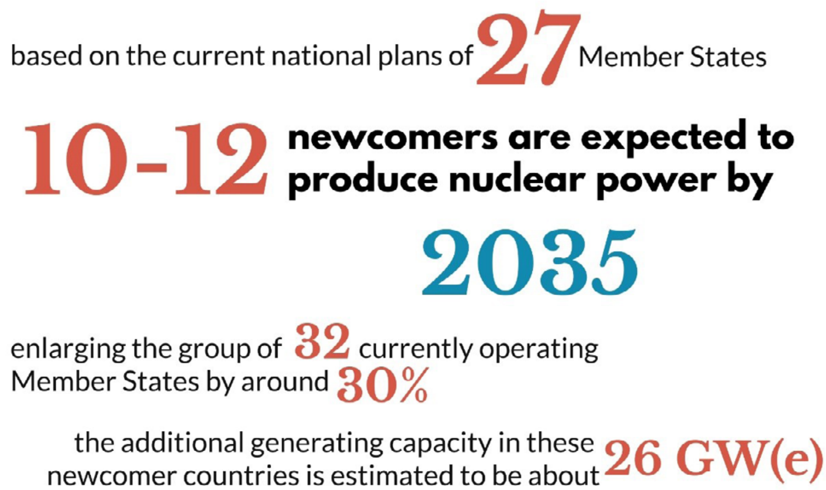


COVID19 travel restrictions and border closures hindered the ability of contractors to support new build projects. This led to the broader use of remote and hybrid verification. Some national regulators applied innovative approaches during the pandemic or adjusted the scope of regulatory inspections based on their safety significance.

Among the 50 Member States that have expressed interest in introducing nuclear power, 23 are in a pre-decision phase and engaged in energy planning activities. The other 27 are pursuing the introduction of nuclear power:

- 17 in a decision-making phase, i.e. those considering nuclear power, including those actively preparing the infrastructure without having made a decision (Algeria, Bolivia, Chile, El Salvador, Ethiopia, Indonesia, Kazakhstan, Morocco, Niger, Philippines, Senegal, Sri Lanka, Sudan, Thailand, Tunisia, Uganda, Zambia).
- 10 in a post-decision-making phase, i.e. those having taken a decision and building the infrastructure, or having signed a contract, and are preparing for or have already started construction (Bangladesh, Egypt, Ghana, Kenya, Jordan, Nigeria, Poland, Saudi Arabia, Turkey, Uzbekistan).

Based on the current national plans of the 27 above-mentioned Member States, 10 to 12 newcomers are expected to introduce nuclear power by 2035, enlarging the group of 32 currently operating Member States by around 30%. The additional generating capacity in these newcomer countries is estimated to be about 26 GW(e) by 2035.



In 2020, owing to limitations imposed by the COVID-19 pandemic, only one Integrated Nuclear Infrastructure Review (INIR) mission was hosted, by Belarus (Phase 3 mission). Other planned missions were postponed to 2021 upon the request of the respective Governments: Kenya (follow-up Phase 1), Sri Lanka (Phase 1), Uganda (Phase 1) and Uzbekistan (Phase 2). Furthermore, 15 Member States had active Integrated Work Plans (IWPs). Some Member States were able to undergo IWP annual reviews before the COVID 19 travel limitations were imposed, while the remaining IWPs were reviewed through virtual meetings.

In Bangladesh, major equipment items for Rooppur NPP were delivered and the reactor pressure vessel was forged and tested early in 2020. The commissioning dates were planned for 2023. The construction of two units at Akkuyu NPP in Turkey continued in 2020. The reactor pressure vessel for Unit 1 was shipped from the manufacturing facility and four steam generators were delivered to the site. Commissioning of the first unit is anticipated for 2023. In Egypt, a site licence for the four-unit NPP at El Dabaa was issued and site preparation for construction continued. Construction of the first unit is expected to start in the second half of 2021, subject to regulatory approval.

In Saudi Arabia, the bidding process for the first two large 1000–1600 MW(e) NPP units is expected to start by the end of 2021, and the NPP technology vendor is expected to be selected in 2024, with commissioning of the first unit planned for 2036.

Poland decided to build NPPs with a total of 6.0–9.0 GW(e) of installed capacity using large PWR reactor technology. The construction of the first NPP is planned to start in 2026 and become operational in 2033.

Jordan is pursuing two parallel paths for the development of a nuclear power programme with SMRs and a large NPP (1000 MW(e) on a build–operate–transfer/build–own–operate–transfer basis), giving priority to SMRs. The first concrete is expected to be poured by 2026, with commercial operation beginning in 2031.

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 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.

Trends

New build projects, whether in countries that already use nuclear power or in newcomer countries, face two challenges on the economic front: the competitiveness of nuclear power compared with alternative energy technologies, and access to finance to cover the investments that nuclear power projects require.

With relatively few new build projects in the last decade, the nuclear sector has not yet enjoyed the kind of major cost reductions experienced by renewable technologies, whose deployment has been facilitated by significant policy and financial support. This has affected nuclear power's competitiveness from the point of view of levelized costs. However, it is increasingly clear that technology costs should also include the cost of their integration in future electricity systems, including grid costs, as well as back-up or energy storage costs. At the system level, nuclear power can be competitive against renewables and storage solutions. In addition, the nuclear industry sees potential in reducing construction costs through simplified designs, enhanced standardization, better supply chain oversight and taking full advantage of the lessons learned from first-of-a-kind projects.

The second challenge relates to access to finance. Nuclear new build projects are capital intensive by nature, and few utilities can finance projects from their own assets. Policy support can help secure financing in many ways, by reducing risks for project developers, whether during construction or operation, to secure revenues against uncertain market conditions, for example through power purchase agreements (PPAs). (In PPAs, the purchaser agrees to take a contracted amount of electricity at a fixed price covering the full cost of the project plus a margin, or pays a penalty.)

Several newcomer countries have included SMR designs in their technology assessments, including Estonia, Ghana, Jordan, Kenya, Saudi Arabia and Sudan. SMRs may have advantages over large reactors, such as lower upfront capital costs, applicability to smaller grids and modular expansion possibilities. The successful deployment of SMRs in the next decade or so could encourage more embarking countries to consider them.

A.4. Nuclear Power Technology Development

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, and the vast majority of the world's nuclear reactors under construction are cooled with light water.

Advanced WCRs are also increasingly considered, studied and implemented in several countries for the gradual deployment of advanced and more efficient fuel cycles, whether partially or fully closed. Several Member States are conducting research and development (R&D) on supercritical water cooled reactors (SCWRs). The conceptual designs of the Canadian SCWR, a heavy water moderated pressure tube reactor, and of the Chinese CSR1000 were completed. In Europe, the concept of the high performance light water reactor (HPLWR) was created, and an in-pile fuel qualification test facility was planned, designed and analysed in collaboration with China. In the Russian Federation, conceptual studies on an innovative water cooled, water moderated power reactor (VVER) with supercritical parameters of water coolant were ongoing, including 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 were targeted in the design phase of evolutionary large WCRs. There is a clear trend towards multi-unit sites with the same or different types of reactors, underscoring the economies of scale for commercial nuclear reactors. In the newcomer countries considering building NPPs, 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

By the end of 2020, at least 16 Member States had active national programmes for SMR design and technology development, most of them carried out as part of international collaboration. Global activities on technology development of SMRs for near term deployment made tangible progress. Major milestones were reached in the operation of SMR technology[5].

In the Russian Federation, the Akademik Lomonosov floating NPP with two KLT-40S units started commercial operation in May 2020 following connection to the grid six months earlier. There were more than seventy SMR designs of major technology lines under development for different applications worldwide. In China, the High Temperature Reactor–Pebble-Bed Module (HTR-PM) (Figure A-1), which will produce 210 MW(e) from two reactor modules connected to a steam turbine generator system was under functional test commissioning for operation in 2021. In Argentina, the CAREM prototype (Figure A-2) was at an advanced

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), IAEA, Vienna (2020).

stage of construction, with the aim of fuel loading and start-up commissioning by the fourth quarter of 2024 to produce 100 megawatt (thermal) (MW(th)) and 30 MW(e) gross. CAREM is an integral PWR type SMR set to operate in natural circulation mode with passive safety features. The design was developed using domestic technology and at least 70% of the components and related services were sourced from Argentinian companies.

FIG. A-1. The HTR-PM in China undertaking system hot functional commissioning, with a view to starting commercial operation in 2022. (Photo: Institute of Nuclear and New Energy Technology, Tsinghua University, China)

FIG. A-2. CAREM is at an advanced stage of construction at a site adjacent to the Atucha II/Néstor Carlos Kirchner NPP in Argentina, for operation by 2024 with a view to producing 30 MW(e) as a prototype demonstration. (Photo: CNEA)

China started site preparation on the 125 MW(e) ACP100, also known as Linglong One, an integral PWR designed as a multi-purpose small power reactor. After about five years of construction, start-up commissioning is foreseen by 2025 for generating electricity, industrial process heat and desalinated water. In the United States of America, the Nuclear Regulatory Commission issued design certification approval for NuScale Power's 50 MW(e) SMR, an integral PWR with natural circulation and full passive safety features. The company subsequently uprated the output of the NuScale Power Module (NPM) to 60 MW(e) before announcing a further uprate to 77 MW(e), for which it plans to seek design certification approval in 2022. The NPM provides power in increments that can be scaled up to 924 MW(e) gross in a single NPP. Construction of the first NPM is expected to begin in the coming years, with operations scheduled to start by 2030 at Idaho National Laboratory.

The Republic of Korea and Saudi Arabia jointly completed pre-project engineering for a system-integrated modular advanced reactor (SMART) that resulted in a preliminary safety analysis report for a 110 MW(e) (365 MW(th)) integral PWR, of which the two countries have design co-ownership. A design change approval is being pursued for SMART to prepare for detailed engineering design for future construction purposes. Japan published the Green Growth Strategy Through Achieving Carbon Neutrality in 2050, which included details on the Japanese Government's active support for international collaboration in demonstrating SMR technologies.

France continued with the development of NUWARD, a PWR-based 340 MW(e) SMR comprising two 170 MW(e) reactor modules with a view to replacing, through this technology, ageing coal-fired power plants over the next decade. NUWARD is characterized by forced convection and advanced safety systems. Likewise, the United Kingdom continued to work on developing technology for the UK SMR, a 450 MW(e) three-loop PWR-based SMR design for domestic and international deployment by 2030.

In the Russian Federation, the 50 MW(e) RITM-200, an integral PWR originally designed and deployed for nuclear powered icebreakers, is being considered for construction as a land-based SMR.

The Canadian Roadmap for SMRs included possible applications for on- and off-grid replacement of fossil and diesel generation plants, including in the oil and mining industries. At least 12 SMR designers/vendors have engaged with the Canadian Nuclear Safety Commission (CNSC) to undertake vendor design reviews of the proposed reactor concepts, including metal cooled fast reactors, molten salt reactors, gas cooled reactors and integral water cooled reactors. An application for a site preparation licence was made by Global First Power for a 15 MW(th) gas-cooled SMR facility at Chalk River Laboratories. The project takes into account both electrical generation and industrial process heat supply. Ontario Power Generation (OPG) recently indicated that it was in the process of selecting an SMR to be deployed at the Darlington New Nuclear Project site in Clarington, Ontario; conditional on provincial approvals, OPG is contemplating an application for a licence to construct in 2022.

Trends

Development activities for a subset of SMRs known as microreactors intensified in several countries, including Canada, the Czech Republic, Japan, the United Kingdom and the United States of America. While there is not yet global consensus on the definition and power range of micro modular reactors (MMRs), there is a general understanding that they will be suitable for providing cogeneration of heat and electricity in remote regions or small islands, and/or to replace diesel generators. One concept undergoing a Nuclear Regulatory Commission (NRC)-led construction licensing process for a project at a US Department of Energy

(DOE) site is the Aurora 1.5 MW(e) fast spectrum reactor being developed by Oklo, a start-up company in the United States of America. In Canada, the Ultra Safe Nuclear Corporation's (USNC's) MMR, with a high temperature gas and prismatic block core designed to produce 15 MW(th) or approximately 5 MW(e), has completed the first phase of the CNSC's vendor design review process and is proceeding with the second phase of the review; and URENCO'S U-Battery, a modular high temperature gas cooled reactor designed to generate 4 MW(e) from 10 MW(th) as a multi-purpose power reactor intends to proceed with a the first phase of the CNSC's vendor design review process.

There is growing interest in Member States in MSRs, with an increasing number of developments. MSR technology gives great flexibility to the designer, giving rise to many possible concepts, such as thermal and fast reactors. MSRs have been designed both as SMRs and large NPPs. Some MSR developers planned to deploy their designs within the next decade. The compact MSR (CMSR) developed by Seaborg Technologies in Denmark completed the basic design and first stage of regulatory approval. In Canada, there are currently two MSR designs proceeding through the CNSC's pre-licensing vendor design review process: Terrestrial Energy's Integral Molten Salt Reactor (IMSR-400, of 195 MW(e)) was in the second phase of the CNSC's vendor design review process; and the Moltex Energy stable salt reactor wasteburner (SSR-W300), designed in Canada and the United Kingdom, was in transition from conceptual design to system level design and was in the first phase of the CNSC's vendor design review process. Several other MSR concepts are in various stages of development in other countries and may be deployed in the coming years.

Several countries engaged in the development of marine-based reactors. The Russian Federation developed four SMR designs for floating power units and one design, 'SHELF', for a subsea immersible power unit. China had at least one design, ACPR50S, to supply electricity for offshore oil and gas platforms. Towards the end of 2020, the Republic of Korea announced the development of BANDI 60, a PWR-based floating power unit.

The common objective of SMR development is to demonstrate that modular construction can achieve lower upfront capital costs through economies of serial production, and that design simplification and shorter construction times can lead to affordable financing schemes. To assist Member States in achieving a common understanding of their needs and specificities regarding SMR technology, the Agency initiated the development of generic user requirements and criteria for SMR design and technology. This document is intended to provide a set of key policy, technical and economic requirements to facilitate 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.

The Agency strengthened its efforts to support Member States interested in carbon-free hybrid energy systems integrating variable renewable energy sources, SMRs, energy storage and non-electric applications. Many countries considered that SMRs, typically with an output of under 300 MW(e), could become an effective source of carbon-free electricity to replace ageing fossil plants. Furthermore, with the higher share of intermittent renewable energy on all continents, SMRs are considered suitable for providing both baseload and flexible operations in synergy with renewables to ensure the security of energy supply.

International Initiatives on Innovative Nuclear Energy Systems

Established in 2000, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is a key vehicle for international cooperation on nuclear energy sustainability, long term strategies, and institutional and technical innovations.

In 2020, INPRO released a suite of tools to provide countries with online fuel cycle assessment capabilities under its new Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES) service.

It also produced a new e-learning course to support experts worldwide in using tools and methods for nuclear energy scenario modelling, comparative systems evaluation and road mapping towards sustainable nuclear energy. And INPRO started a collaborative project using ASENES to create case studies on sustainable deployment scenarios specifically for SMRs.

A.4.3. Fast Neutron Systems

Status

Several countries with advanced nuclear power programmes continued to develop fast neutron systems in line with their national programmes. Two industrial sodium cooled fast reactors (SFRs) continued operating in the Russian Federation: the BN-600 (since 1980) and the advanced BN-800 (since 2016). The BN-1200 reactor, which is under design, will follow a series of Russian SFRs targeting the enhanced safety level established for innovative reactors by the Generation IV International Forum. India was completing commissioning of its sodium cooled Prototype Fast Breeder Reactor. Since 2010, China has operated the 20 MW(e) sodium-cooled China Experimental Fast Reactor. The innovative CFR-600, of the SFR type, has been under construction since 2017. Construction work has started on the second CFR-600 sodium cooled, pool type, fast neutron reactor in Xiapu County, Fujian, China. Also known as the Xiapu fast reactor demonstration project, the CFR-600 is part of China's plan to achieve a closed nuclear fuel cycle. France, despite its long history of developing and operating SFRs, postponed plans to build a prototype innovative SFR (the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID)), focusing instead on an R&D programme. Japan has promoted competition among various fast neutron reactor technologies, including SMRs, by conducting feasibility studies in its Nuclear Energy x Innovation Promotion (NEXIP) programme, as the first phase of its Strategic Road Map for Fast Reactor Development. The next target of the road map is to demonstrate technology in the middle of the 21st century.

In the Russian Federation, the lead cooled BREST-OD-300 and the lead–bismuth cooled SMR SVBR-100 were undergoing licensing. Some European Union countries were jointly developing the Advanced Lead Fast Reactor European Demonstrator (ALFRED), which Romania offered to build at the Mioveni site. In the United Kingdom, the design review for the Swedish Advanced Lead Reactor (SEALER) 55MW(e) SEALER-UK plant was pending with the UK Department for Business, Energy and Industrial Strategy.

In 2020, General Atomics and Framatome jointly announced a new conceptual design for a helium cooled 50 MW(e) fast modular reactor. The European Union continued the development of ALLEGRO, an experimental helium cooled fast reactor. TerraPower and GE Hitachi Nuclear Energy announced Natrium (Figure A-3), a new advanced hybrid technology featuring a 345MW(e) SFR combined with a molten salt energy system that can be used to boost the total output to 500MW(e).

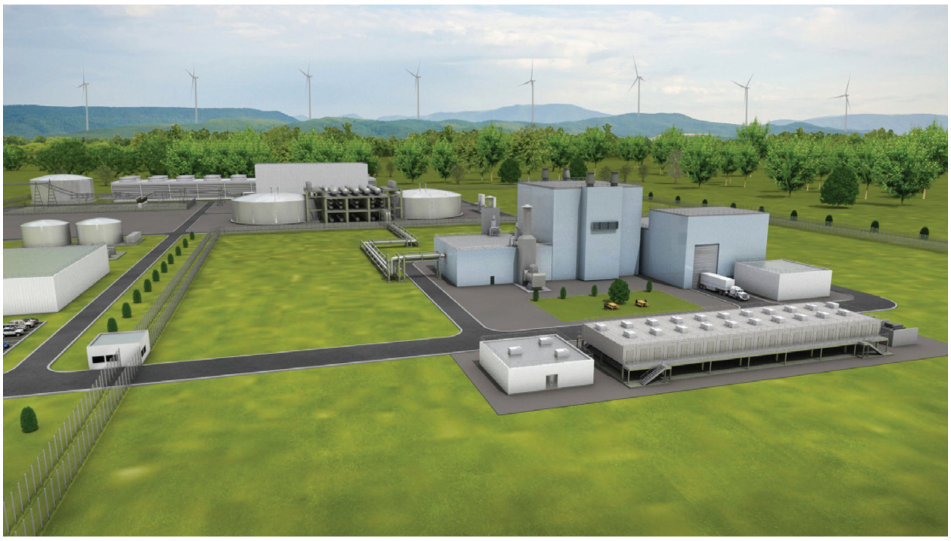


FIG. A-3. The Natrium advanced hybrid technology developed by TerraPower and GE Hitachi Nuclear Energy. (Source: TerraPower)

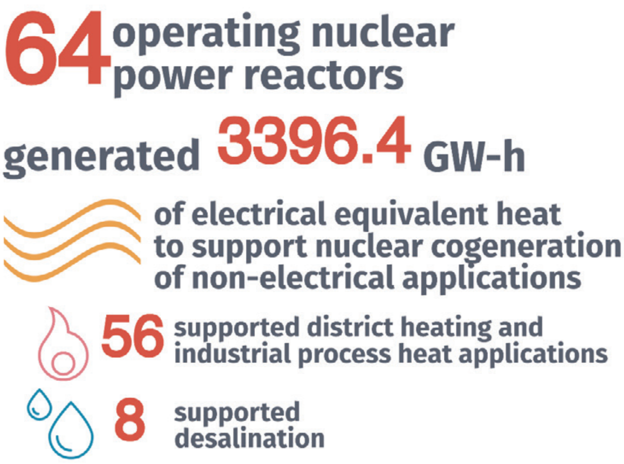
Trends

Almost all new fast neutron concepts and innovative designs were proposed as SMRs. Along with mature sodium technology, new fast reactor designs and concepts are being developed. Additionally, fast reactors cooled by heavy liquid metals, such as lead and lead–bismuth eutectic, attracted growing interest. Helium is another coolant considered as an alternative for fast neutron systems. Although fast neutron systems face some technological challenges, their economic competitiveness is still recognized as the primary obstacle to their deployment. Still, the potential of these reactors to significantly reduce the volume, toxicity and lifespan of radioactive waste, and to get more out of nuclear fuel, combined with new concepts, continued to drive their technological development.

A.4.4. Non-electric Applications of Nuclear Power

Status

A total of 64 operating nuclear power reactors were used to generate 3396.4 gigawatt-hours (GWh) of electrical equivalent heat for non-electric applications. Fifty-six reactors supported district heating and industrial process heat applications and 8 supported desalination.



Hydrogen production

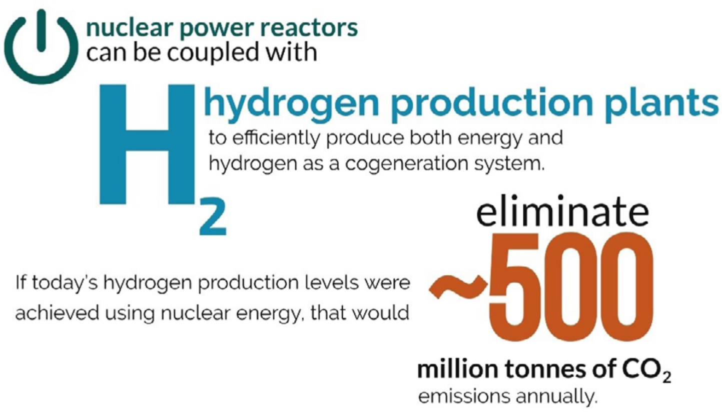
Major advancements were recorded in the field of nuclear hydrogen production.

In the area of nuclear hydrogen production, several Member States increased their focus on the use of off-peak power from light water reactors to produce hydrogen. The DOE contracted utility companies Energy Harbor, Xcel Energy and Arizona Public Service to demonstrate hydrogen production at three NPPs in 2020 and 2021 in projects involving several national laboratories. In the United Kingdom, EDF Energy is leading the 'Hydrogen to Heysham (H2H)' project to produce low carbon hydrogen using nuclear power.

In China, advances were made in R&D on nuclear hydrogen production. The Shanghai Institute of Applied Physics completed long-term testing of the 5 kilowatt (kW) solid oxide electrolysis cell (SOEC) stack with stable performance and established a 20 kW hydrogen plant using high temperature steam electrolysis technology. New targets were focused on SOEC and stack manufacture, as well as 200 kW and megawatt scale plant demonstration projects, coupled to a thorium MSR to achieve large-scale hydrogen production.

Canadian Nuclear Laboratories continued development of the hybrid thermochemical copper chlorine technology for nuclear hydrogen production. The target is an integrated laboratory-scale system for demonstration, working towards scaling up to a prototype plant. Japan achieved closed-loop automated continuous hydrogen production through the iodine–sulphur thermochemical water splitting process at rates of up to about 30 litres/hour and for time periods of up to 150 hours, which will eventually lead to hydrogen production utilizing heat at more than 900 degrees Celsius, produced at very high temperature gas cooled reactors in the future. Important data were obtained to investigate material and component performance and reliability, and to improve fluid and reaction control techniques necessary to achieve longer-term operations.

In the area of district heating using NPPs, the Russian Federation made a breakthrough in launching the Akademik Lomonosov floating NPP. The plant can supply electricity to oil rigs off the Russian Federation's Arctic coast and supply power to a desalination plant to produce fresh water as well as heat for district heating, as required. The Akademik Lomonsov NPP will gradually replace Bilibino NPP (Figure A-4), which has received an extension to operate for five more years. Bilibino NPP, one of the oldest nuclear cogeneration plants in the world, provides electricity and heat for the city of Bilibino. Other countries, such as China and the Republic of Korea, announced plans to develop their own floating NPPs.



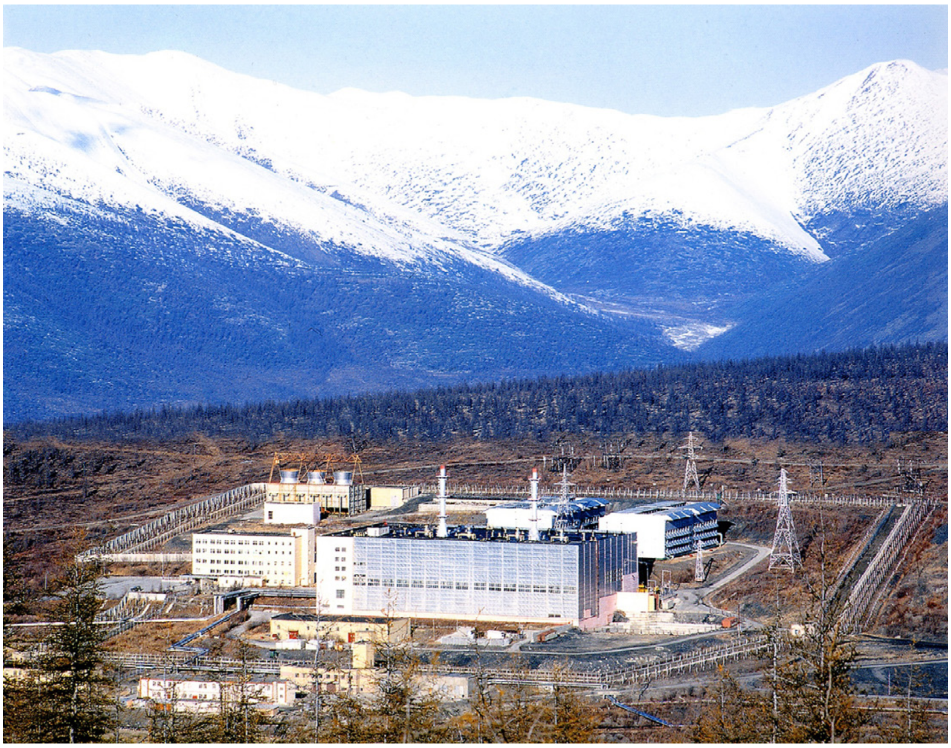


FIG. A-4. Bilibino NPP, used for cogeneration of heat and electricity in the Russian Federation. (Photo: Rosenergoatom)

Trends

The use of nuclear energy beyond electricity production is gaining unprecedented momentum worldwide. In addition to its role in decarbonizing end-use sectors, such as transport, industry or the residential sector, nuclear cogeneration is increasingly seen as an opportunity to build an economic case against the early retirement of non-profitable NPPs, particularly amid growing shares of variable renewable energy systems in electricity grids. Interest in nuclear hydrogen production using water cooled reactors is expected to continue towards the commercial stage, especially if demonstration projects are successful.

However, challenges related to infrastructure issues concerning storing and transporting hydrogen will first need to be addressed. Lessons learned from ongoing projects carried out by different countries are expected to expedite the upscaling of nuclear hydrogen production using conventional electrolysis. The development of highly efficient processes for nuclear hydrogen production is also likely to continue. The concept of using nuclear energy for non-electric applications as a standalone plant, cogeneration, or as part of integrated energy systems with renewable sources for multi-purpose applications is expected to be a trend to watch in the coming years. Such applications include the production of fresh water, the generation of hydrogen as a fuel and energy carrier, and district heating and cooling for residential and commercial buildings, as well as for serving many other industries, including steelmaking, petrochemical refineries and production of synthetic fuels.

The Agency has established the Hydrogen Economic Evaluation Program and the Hydrogen Calculator and an IAEA Toolkit for Nuclear Hydrogen Production to support Member States in their techno economic evaluations of hydrogen production using nuclear energy as compared to other alternatives.

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

Status

The fusion community celebrated the start of ITER machine assembly and integration (Figures A 5 and A 6) after more than ten years of complex construction phases, involving site preparation and design and manufacturing of key systems and components. Progress towards the ITER project's first plasma operations scheduled for December 2025 was about 70% complete at the end of 2020. Once in operation, ITER will provide much of the scientific and technological basis for the development and design of future fusion power reactors capable of energy production.

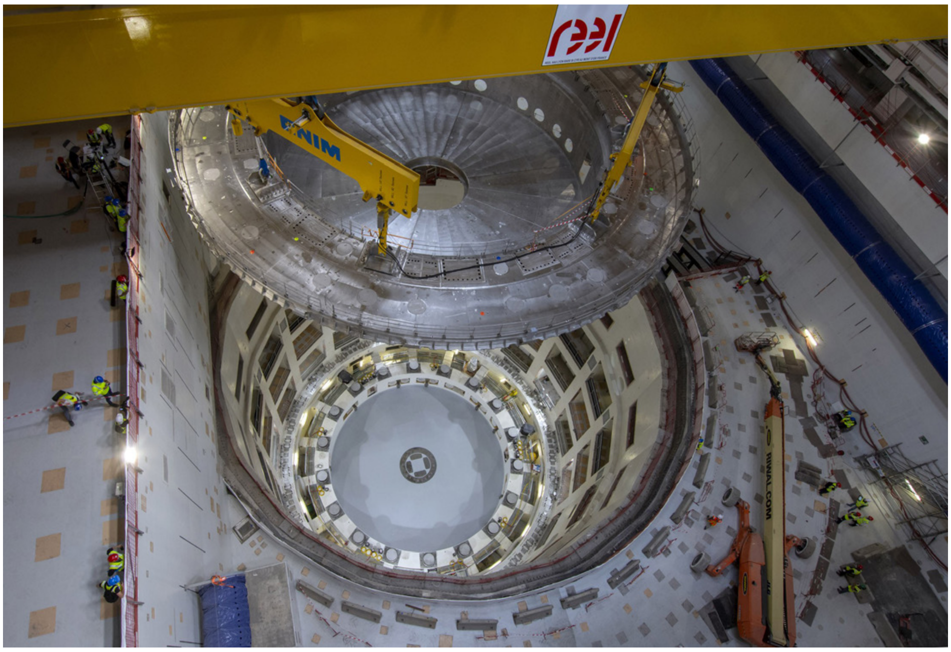


FIG. A-5. The 1250-tonne cryostat base was the first large-scale component to be installed at the bottom of the 30-metre-deep Tokamak assembly pit. (Photo: ITER Organization)

FIG. A-6. After the cryostat base was installed, the 375-tonne cryostat lower cylinder was lowered to the bottom and welded to the base. (Photo: ITER Organization)

The Joint European Torus (JET), a tokamak with enhanced heating power and an ITER-like wall, has been preparing for the tritium experimental campaign, aimed at testing and preparing for the next experiments with an equal mix of deuterium (D) and tritium (T). The JET DT experimental campaign, scheduled to start during the summer of 2021, is to provide a unique physics and technology basis for ITER's operation. One of its main performance goals is to generate 15 MW of thermal power for about 5 seconds in stationary conditions in order to study the key physics aspects of fusion energy production.

In the area of inertial fusion confinement with high-power lasers, the National Ignition Facility in the United States of America has continued improving experiment performance by increasing the energy coupling efficiency from laser energy to energy absorbed by the fuel capsule, identifying several sources of energy leaks and developing mitigation techniques to enable higher performing experiments. Increasing the coupling efficiency is advantageous for improving the prospects for energy production.

Trends

Investment in publicly and privately funded fusion research and technology keeps growing. Over 90 publicly funded fusion devices are in operation, under construction or being planned (Figure A-7). In addition, more than 20 private sector fusion companies are researching and developing a variety of smaller-scale devices and approaches based on different fuels, alternative confinement geometries and new technologies such as high temperature superconducting magnets.

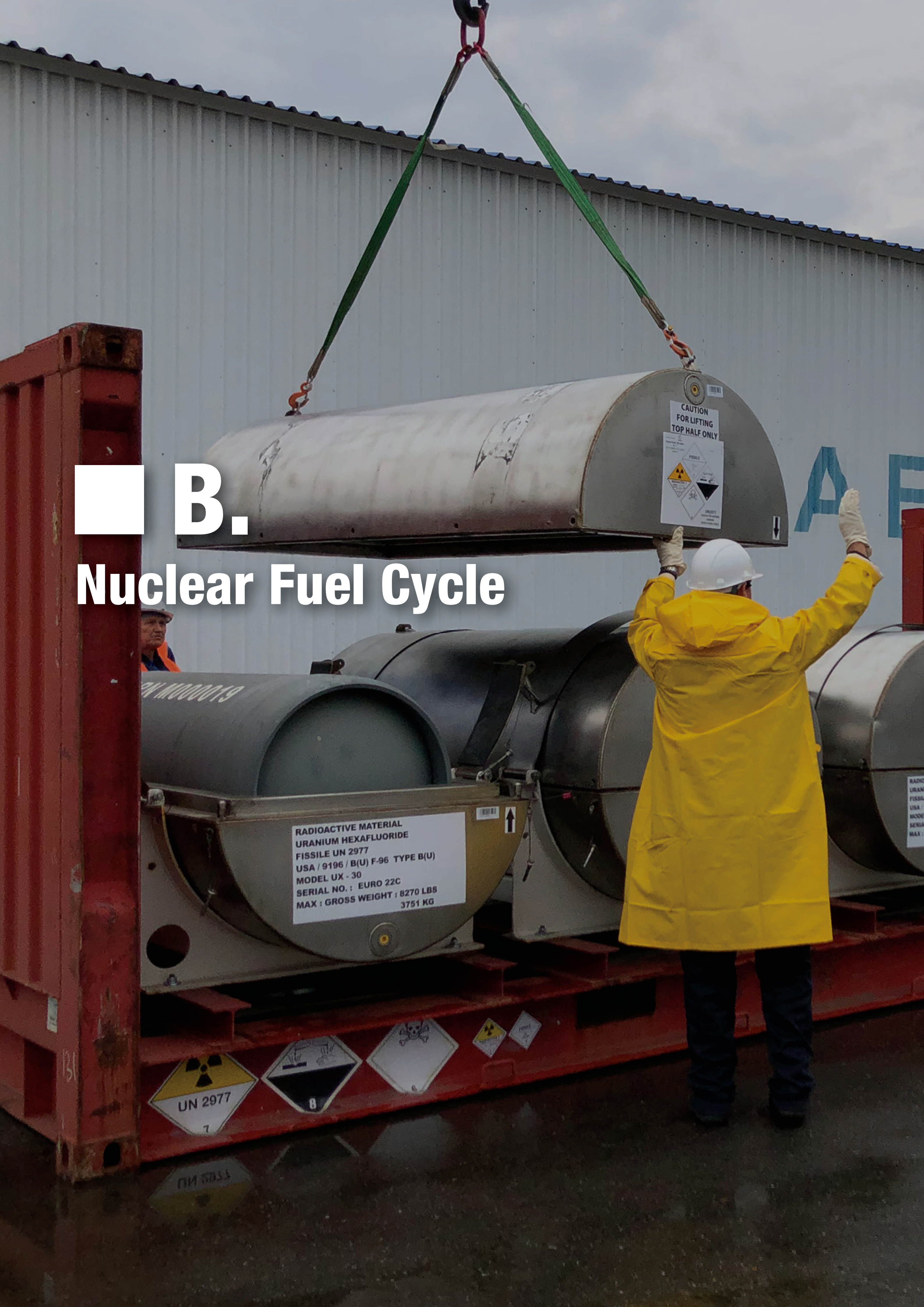
The DOE, the US Nuclear Regulatory Commission and the Fusion Industry Association hosted a virtual Public Forum on a Regulatory Framework for Fusion. The purpose of the forum was to begin a dialogue on a regulatory framework addressing future plans for development and establishment of fusion energy reactor systems, supported by either the public or private sector with US and other national regulating bodies.

FIG. A-7. Over 100 fusion devices (public and private) are currently in operation, under construction or being planned. (Source: Fusion Device Information System)

Some specific experiments to address issues related to materials behaviour under plasma exposure, as well as corrosion, are being carried out as part of newly developed materials and technology plans, such as the Materials Plasma Exposure eXperiment at Oak Ridge National Laboratory in the United States of America and under the EUROfusion 'MAT' programme in Europe. Furthermore, in the absence of dedicated irradiation facilities for fusion materials research, key results are being obtained in irradiation campaigns carried out in research reactors such as the High Flux Isotope Reactor at Oak Ridge National Laboratory as a collaboration between the European Union, Japan and the United States of America.

The DOE's Office of Fusion Energy Sciences awarded US $18 million to fund operations and user support at high-intensity laser facilities in the United States of America and Canada through 'LaserNetUS', an initiative established in 2018 to provide scientists at universities and national laboratories with increased access to these facilities. In Japan, the Laser Fusion Strategy Committee, composed of around 40 members from 20 institutes, is considering the development of a high-repetition laser system to perform data-driven analysis of fusion plasmas, as well as the testing of laser fusion reactor engineering using a fusion based neutron source. In Canada, General Fusion has been developing magnetized target fusion technology for the past ten years and has publicly indicated plans to establish a demonstration facility. General Fusion has approached the CNSC to request pre-licensing engagement activities to understand how the licensing process would proceed. CNSC is also conducting pre licensing discussions with start-up companies that are seeking to conduct fusion research and development activities as part of technology development.

B. Nuclear Fuel Cycle



B. Nuclear Fuel Cycle

B.1. Front End

Status

As a result of the global COVID-19 pandemic, several major uranium producers suspended operations or significantly reduced production. More than 90% of the world's uranium production is concentrated in Australia, Canada, Kazakhstan, Namibia (Figure B-1), the Niger, the Russian Federation and Uzbekistan. With reduced global uranium production, the undersupply — a deficit made up by secondary supplies — resulted in an increase of the spot price by 41% in the first quarter of 2020. However, this was still below the price required to restart idle mines or develop new uranium mines. The spot price for uranium decreased by about 15% in the third quarter of 2020, with the resumption of mining at the Canadian Cigar Lake uranium mine (the world's largest uranium producer) in September, following a five month shutdown owing to the global pandemic.

FIG. B-1. Aerial view of the open-pit mine at Husab uranium mine, Namibia. (Photo: Swakop Uranium)

Accident tolerant fuels or advanced technology fuels under development in Europe, Japan, the Russian Federation and the United States of America sometimes require higher uranium-235 enrichments to compensate for the loss of neutronic transparency of their cladding materials. Therefore, high assay low enriched uranium (HALEU) fuels, enriched above 5% but below 20%, are being tested.

Global Nuclear Fuel accident tolerant fuel assemblies were loaded into a US reactor for the first time. Lead test assemblies using the company's 'ARMOR'-coated zirconium cladding and 'IronClad' accident tolerant fuel solutions were installed at Exelon's Clinton NPP in the United States of America.

The first Russian-made nuclear fuel assemblies with experimental accident tolerant fuel rods for commercial reactors were manufactured and passed acceptance inspection at Novosibirsk Chemical Concentrates Plant, a fabrication facility of Rosatom's fuel manufacturer subsidiary TVEL Fuel Company. The fuel rods were loaded into one of the VVER-1000 units at the Rostov NPP in the Russian Federation.

Lead test assemblies of accident tolerant fuel installed in Unit 1 of Southern Nuclear's Edwin I. Hatch NPP in early 2018 completed a 24-month fuel cycle, and a sample of the lead test rods will now undergo testing. An initial inspection of the rods has already been completed. The rods' material and coating properties will be further evaluated at the DOE's Oak Ridge National Laboratory.

Lead test assemblies of EnCore accident tolerant fuel were installed in ENGIE Electrabel's Doel NPP Unit 4 in Belgium. Doel-4 is the second commercial reactor in the world, and the first in Europe, into which EnCore assemblies have been installed.

TerraPower announced plans to team up with nuclear fuel and services provider Centrus Energy to establish commercial-scale, domestic production capabilities for HALEU. This will be needed to fuel many next generation reactor designs, including the recently announced Natrium power storage system designed by TerraPower and GE Hitachi Nuclear Energy.

The manufacture of the first full reload batch of uranium–plutonium mixed oxide (MOX) fuel (Figure B-2) for Unit 4 of the Beloyarsk NPP in the Russian Federation was completed by the Mining and Chemical Complex in Zheleznogorsk, Russian Federation. The 169 fuel assemblies have been accepted by the operator, Rosenergoatom, and its authorized representative, ZAES.

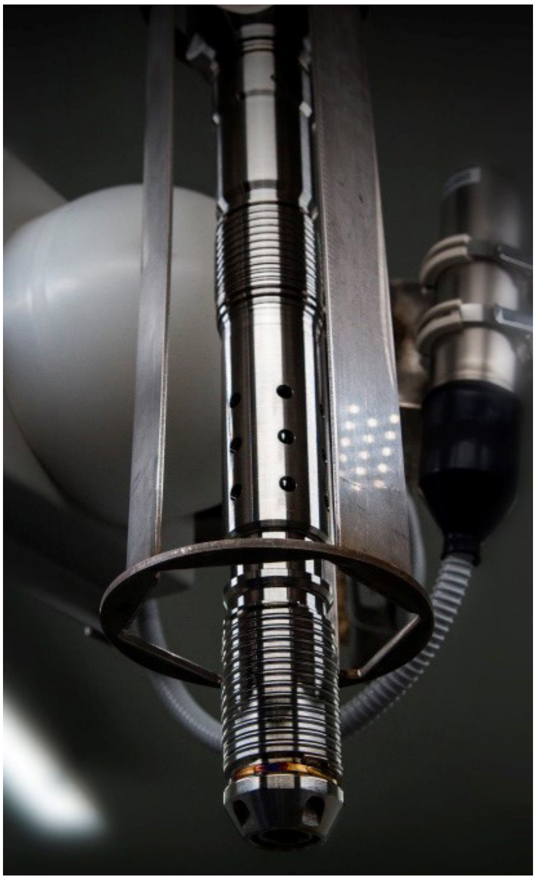


FIG. B-2. A MOX fuel assembly for the BN-800 fast reactor. (Photo: Mining and Chemical Combine Complex, Russian Federation)

Canadian Nuclear Laboratories entered into four collaboration agreements with SMR technology developers under its Canadian Nuclear Research Initiative. The first is with USNC-Power, a subsidiary of USNC, on research in support of USNC's MMR. The project will include research related to the manufacturing of USNC's Fully Ceramic Microencapsulated fuel. The second is with UK based Moltex Energy on work to support aspects of Moltex Energy's nuclear fuel development programme for its stable salt reactor, a 300 MW(e) SMR. The third is with US based Kairos Power on research and engineering of technologies to better separate, analyse and store tritium generated through the operation of Kairos Power's proposed SMR design. The fourth agreement is with Terrestrial Energy to develop and test techniques to track the behaviour of the proposed liquid fuel that would be used in Terrestrial Energy's Integral Molten Salt Reactor design.

Holtec International selected Framatome to supply nuclear fuel for its SMR-160 reactor. The companies have entered into an agreement to enable completion of all necessary engineering to fuel the SMR-160 with Framatome's commercially available and proven 17x17 GAIA fuel assembly.

X-Energy's tristructural isotropic (TRISO) fuel, TRISO-X, started irradiation at the Massachusetts Institute of Technology Nuclear Reactor Laboratory's research reactor. Data from the irradiation testing will be used to support the licensing of X-Energy's Xe-100 and other TRISO-based reactors.

The USNC established a new facility in Salt Lake City, Utah, United States of America, to support the development of its proprietary Fully Ceramic Microencapsulated fuel, a next-generation uranium oxycarbide TRISO particle fuel design, replacing the 50-year-old graphite matrix of traditional TRISO fuel with silicon carbide. Materials developed at the new facility will be used in the USNC's MMR and other nuclear reactors, including gas cooled reactors, light water reactors, CANDU reactors and molten salt cooled reactors.

A contract with the China Nuclear Energy Industry Corporation (CNEIC) concerning the transport of low enriched uranium (LEU) and/or equipment necessary for the operation of the IAEA LEU Bank, was signed, providing for a second route of transportation to and from the Bank. The IAEA LEU Bank, located in Kazakhstan, has been operational since October 2019. Other assurance of supply mechanisms in place are described in the *Nuclear Technology Review 2012* (document GC(56)/INF/3).

Trends

Overall, primary uranium supply was lower in 2020, with a forecast production of about 46 500 tonnes. This represents about 69% of global demand for uranium, thereby putting more pressure on secondary uranium supplies to fill the demand for uranium as nuclear fuel.

To ensure a sustainable supply of nuclear fuel for current and future NPPs, the world will require more uranium mines. Based on historical records, very few of the identified uranium deposits are expected to advance to mining and production owing to economic, technical, environmental or social constraints. Therefore, innovation is required to advance marginal uranium deposits into production. One example of such innovation in the uranium mining industry in 2020 was the ongoing evaluation of in situ recovery technologies 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. China has been undertaking research on this technology over the past decade in order to improve recovery and remediation for these deposit types.

The use of high burnup fuel in the existing NPP fleet is considered to be an option for improving the sustainability of the fuel cycle, since the annual consumption of natural uranium is reduced with extended discharge burnup.

B.2. Back End

Status

According to feedback from the Agency's COVID 19 NPP OPEX Network, the operation of spent fuel storage facilities was not significantly affected by the pandemic, except for fuel outages that in some cases prompted delays. Spent nuclear fuel in storage is globally accumulating at a rate of approximately 7000 tonnes of heavy metal (t HM) per year, while the stored inventory is approaching 300 000 t HM.

Spent MOX fuel was removed from the Ikata NPP, in the first such operation in Japan, and a month later from the Takahama NPP. The spent MOX fuel rods will temporarily be stored in a cooling pool. The government of Japan is conducting R&D related to reprocessing of this fuel, in accordance with its energy policy.

For countries with long-established nuclear programmes pursuing open cycle strategies, the main challenge is the decreasing capacity for on-site spent nuclear fuel storage and the increasing storage duration (more than 100 years).

The expansion of dry storage capacity at the Wolsong NPP in the Republic of Korea was approved in January 2020. This was an important step, given that the existing storage capacity was nearly fully utilized.

The NRC issued a draft of the environmental impact assessment for the planned centralized interim storage facility in New Mexico, United States of America.

After the delivery of the last storage cask for spent nuclear fuel one year ahead of schedule, the shutdown Ignalina NPP in Lithuania reached its full capacity to safely manage and store, on site, all spent nuclear fuel from its two RBMK-1500 reactors.

Trends

The Agency coordinates research activities to enhance understanding of the ongoing behaviour of spent nuclear fuel in various storage systems and the ageing and degradation mechanisms of storage systems themselves. This will help ensure that spent nuclear fuel can continue to be stored safely and transported to a disposal and reprocessing facility.

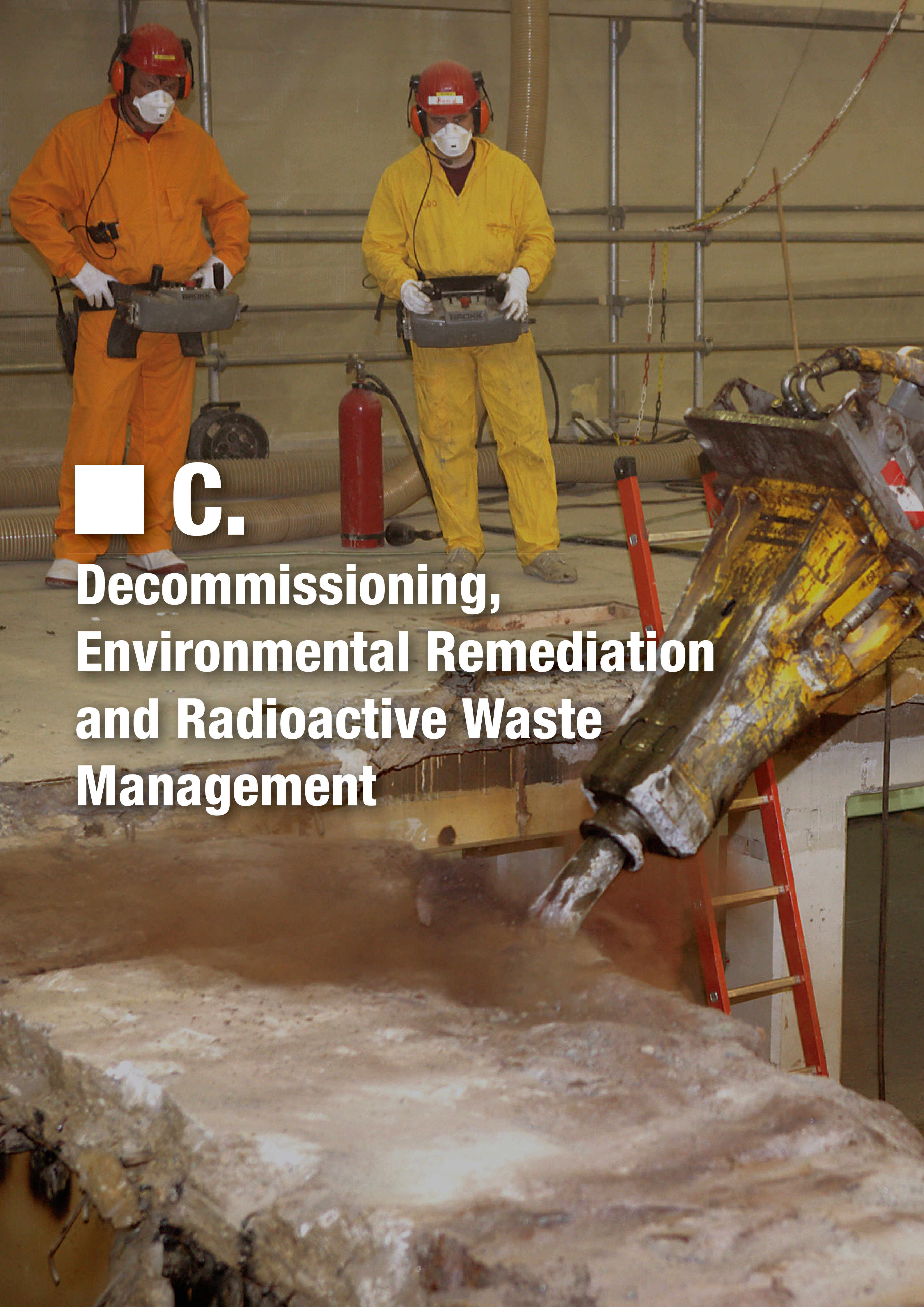
Efficiency gains in the management of nuclear reactors have resulted, over time, in less spent nuclear fuel being discharged from nuclear reactors. However, this is with higher initial enrichments and higher burnups, resulting in greater residual heat and higher cladding embrittlement risks, which may impact spent nuclear fuel management steps.

New fuel designs to be deployed in the near future, with higher enrichments of up to 8% and coated cladding materials, will present potential challenges to existing storage systems, as their behaviours in the longer term need to be understood to properly analyse the safety of all spent nuclear fuel management steps, including storage, transportation and disposal.

Spent fuel is considered a valuable energy resource by some countries, and developments in recycling technologies are in progress. Advanced processes for plutonium multi-recycling (CORAIL and MIX in France, and REMIX in the Russian Federation) in light water reactors are undergoing demonstration to enable the transition to plutonium multi-recycling strategies in fast reactors. These recycled fuels are expected to enable a more effective use of natural resources, reduce the volume and radiotoxicity of the nuclear waste generated, and lower proliferation risks.

C.

Decommissioning, Environmental Remediation and Radioactive Waste Management

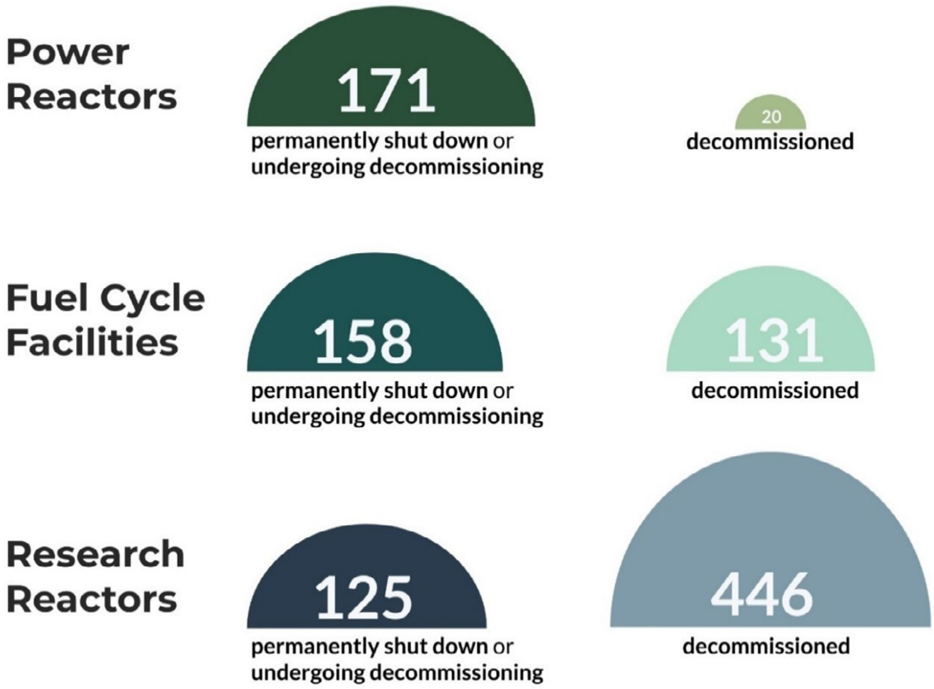


C. Decommissioning, Environmental Remediation and Radioactive Waste Management

C.1. Decommissioning

Status

Six nuclear power reactors were permanently shut down in 2020: Fessenheim Units 1 and 2 in France, Leningrad 2 in the Russian Federation, Ringhals 1 (an 881 MW(e) BWR) in Sweden and Duane Arnold 1 and Indian Point 2 in the United States of America. That was fewer than in 2019, when 13 reactors ended operation. By the end of 2020, a total of 171 reactors had been shut down or were undergoing decommissioning. Of those, 20 reactors had been decommissioned. There were also 158 fuel cycle facilities and 125 research reactors under permanent shutdown or undergoing decommissioning worldwide. Some 131 fuel cycle facilities and 446 research reactors had been decommissioned.



The largest ongoing NPP decommissioning programmes were in Germany, Japan and the United States of America. Germany had 26 NPPs under decommissioning, while the remaining 6 operating NPPs are to be shut down permanently by the end of 2022. Decommissioning began at Gundremmingen Unit B and at Philippsburg Unit 2 following receipt of decommissioning licences during 2019. The Great East Japan Earthquake in 2011 led to the permanent shutdown of a significant proportion of Japan's nuclear fleet. In 2020, a total of 24 of Japan's 60 commercial NPPs were either in permanent shutdown or already under decommissioning. The United States of America, where several reactors have been permanently shut down during the past decade for reasons of unprofitability, had 18 active decommissioning programmes. Of these, seven facilities were following an immediate dismantling strategy, seven were in safe enclosure and a further four were transitioning from safe enclosure to immediate dismantling. Three US plants were scheduled to complete decommissioning in 2020: La Crosse (Wisconsin), Humboldt Bay (California), and Zion (Illinois).

Important progress was achieved in the Chornobyl and Fukushima decommissioning projects. In September 2020, hot tests commenced at the new Interim Spent Nuclear Fuel Storage Facility (Figure C 1) adjacent to Chornobyl NPP, while the Free Release Facility for waste, with a throughput capacity of ten tonnes per day, began operation.

FIG. C-1. The first double-wall shielded canister filled with 93 spent fuel assemblies is leaving the Spent Fuel Processing Facility to be placed for the one-hundred-year storages. (Photo: State Specialized Enterprise Chornobyl NPP)

Japan reported that the water with a reduced strontium content, previously stored in tanks awaiting treatment by the Advanced Liquid Processing System (ALPS) had been completely treated by August 2020, and the tanks would be reused for storing the ALPS treated water. The Government of Japan is still considering several options for handling of the ALPS treated water, including vapour release or discharge into the sea, but has yet to make a final decision.

In France, decommissioning advanced at the site of La Hague (Figure C 2), where Orano's UP2 400 reprocessing plant was being dismantled. Operational teams began the retrieval of 600 tonnes of legacy graphite and magnesium waste stored in concrete silos, guided by a sorting system using technology based on artificial intelligence, while dismantling activities continued at the main plant. Dismantling of the plutonium finishing workshop dry gloveboxes was completed. Other operations began in order to dismantle a second dissolver in the former dissolution and extraction building, and to dismantle the mechanical hot cells of a former caesium source fabrication workshop. The chemical cells of this workshop had been dismantled in the previous three years using remotely operated equipment.

FIG. C-2. Aerial view of the Orano site in La Hague, Normandy, France. (Photo: Orano)

Électricité de France began construction of a demonstration facility for graphite reactor decommissioning. It is expected to be in operation by 2022 to facilitate testing of dismantling technologies for graphite moderated reactors. In the Russian Federation, Rosatom planned to follow an entombment strategy for decommissioning its early uranium graphite reactors as an exceptional case and is proceeding with the construction of a demonstration centre to test this approach. This facility is expected to be operational by 2021.

Sogin, Italy's State-owned company responsible for decommissioning, started preliminary activities for the decommissioning of the ISPRA-1 research reactor at the site of the Joint Research Centre of the European Commission.

Trends

While in previous decades deferred dismantling was the dominant decommissioning strategy adopted by facility owners, an immediate dismantling approach has been gaining favour. Moreover, timeframes for beginning final dismantling of retired plants are increasingly being brought forward, with a number of deferred dismantling strategies being changed to immediate dismantling. This change has been driven by a desire to reduce uncertainties over decommissioning costs.

There is growing involvement of specialist decommissioning and waste management consortia that seek to deliver entire decommissioning projects. For example, there have been recent cases in the United States of America where licence responsibility and entire decommissioning funds are being transferred from the utility to the decommissioning consortium, which, in turn, takes over full responsibility for project delivery.

Another trend is an increased use of digitalization, robotics and automation, including for planning and simulation, plant configuration management and knowledge management, as well as to support implementation of waste retrieval, characterization and dismantling.

In many cases, the unavailability of a final disposal solution for spent nuclear fuel or the lack of a radioactive waste repository creates a constraint for decommissioning progress. As a result, the construction of facilities for spent fuel and radioactive waste storage on or near the sites of facilities to be decommissioned has become a widely used measure to enable decommissioning to proceed even where facilities for final disposal of these materials are not available. For example, BGZ Company for Interim Storage in Germany is taking over full responsibility for long term storage of spent fuel and radioactive waste, so that facilities can be dismantled as soon as practicable.

C.2. Environmental Remediation

Status

Remediation activities were limited in 2020 owing to the COVID-19 pandemic. However, remediation works continued at sites where there were significant risks to people or the environment or where there was potential for the economic reuse of the site.

Remediation began at the Shekaftar site in Kyrgyzstan on the closure of six shafts and the relocation of five waste rock sites to an existing waste rock site in a more remote location. Approximately 700 000 cubic metres of waste from mining operations located around the local village is to be removed and stabilized in a new location to ensure the protection of people and the environment. The work was funded through the Environmental Remediation Account for Central Asia of the European Bank for Reconstruction and Development, and is part of the wider Strategic Master Plan for Environmental Remediation of Uranium Legacy Sites in Central Asia. During 2020, remediation projects in Kyrgyzstan (Min-Kush site) and Tajikistan (Yellow Hill and tailings piles 1–4 at Istiqlol) carried out in the framework of the Commonwealth of Independent States intergovernmental programme on remediation continued as planned.

In the United States of America, removal of the remaining building slabs on the site of the former Oak Ridge Gaseous Diffusion Plant (Figure C3), was completed, enabling the regulatory approval process for release of the site to the local community for economic development. The completion of the works will enable the release of more than 500 hectares of land for reuse as part of the Manhattan Project National Historical Park.

FIG. C-3. Progress in remediation work made at the site formerly known as the Oak Ridge Gaseous Diffusion Plant in Oak Ridge, Tennessee, United States of America. (Photo: DOE)

Trends

The focus on characterization and monitoring technologies continued to support the transition to long term management and control as an optimization solution for many sites.

The major trend observed in 2020 was the increased application of the concept of the circular economy to naturally occurring radioactive material (NORM) residue management. In this context, the focus is on the secondary, reusable resource, with the purpose of conserving primary resources. An important example of this trend was the recent authorization by the US Environmental Protection Agency that allows phosphogypsum to be used in Government road construction projects. The expansion of similar approaches will require the formation of constructive partnerships that can lead to innovative solutions that also address social and regulatory dimensions.

The first test flight was made under the Development of an Unmanned Aerial Vehicle-Based Gamma Spectrometry for the Exploration and Monitoring of Uranium Mining Legacies (DUB-GEM) project. The research project, funded by the German Federal Ministry of Education and Research, is aimed at supporting the characterization of uranium legacy sites in Central Asia. Generally, the use of relatively small gamma spectrometers on small drones has been focused on surveying highly contaminated areas. However, research is under way to use this configuration to investigate low levels of radioactive contamination. The new systems will explore the use of larger detector volumes, drones with a higher take-off weight of up to 25 kg and new scintillation crystal materials such as cerium bromide. Development of this technology will facilitate the rapid survey of radioactive contamination in mountainous regions that can be difficult to access and traverse, or over larger areas, which can be time consuming.

The experience of nuclear industry to deal with contaminated materials is driving the efforts in other industries dealing with NORM. For example, decommissioning of oil and gas platforms is a major development in the scope of industrial activities related to NORM. There are around 1885 active production platforms in the United States of America outer continental shelf, more than 60% of which are over 25 years old. It is estimated that, between 2016 and 2021, around 600 offshore assets will have been decommissioned globally.

C.3. Radioactive Waste Management

Status

Major advancements continued to be made on the development of deep geological disposal facilities needed for high level waste and spent fuel declared as waste. This included improved awareness of, and early planning for, the required resources, such as the design and implementation of siting approaches supported by scientific and technical developments, engagement with stakeholders, and the sustained provision of these resources.

The United Arab Emirates set up a trust fund dedicated to future waste management responsibilities, making it the first country to have such funding arrangements in place before its first NPP had been connected to the grid.

The Australian Government announced the establishment of the Australian Radioactive Waste Agency (ARWA) as the next important step in developing Australia’s radioactive waste management capabilities. ARWA will work with stakeholders such as industry, community and Government agencies to best manage radioactive waste. Australia's Senate Economics Legislation Committee recommended the passage of the National Radioactive Waste Management Amendment (Site Specification, Community Fund and Other Measures) Bill 2020 through the Australian Parliament. That legislation specifies Napandee in South Australia as the site for a future low and intermediate level radioactive waste facility.

The Belgian Agency for Radioactive Waste and Enriched Fissile Materials conducted a public consultation on a proposed national plan for the final disposal of high activity and/or long lived radioactive waste, which recommends geological disposal.

The Finnish Radiation and Nuclear Safety Authority notified authorities in countries that have supplied uranium to Finnish NPPs that the country intends to begin the final disposal of used nuclear fuel in the mid-2020s. Since normal inspections of nuclear materials cannot be performed after the materials are disposed of, procedures related to such inspections must be specified before the initiation of final disposal. The disposal process at Finland's Onkalo disposal facility, which is being constructed at a depth of over 400 metres below ground level, is planned to start in 2024 (Figure C-4). France and Sweden are engaged in the licensing process of their deep geological disposals at determined sites. Several other countries are moving progressively in their projects on deep geological disposal, including Japan, Switzerland, United Kingdom and the United States of America.

FIG. C-4. The disposal process at the Onkalo disposal facility in Finland is planned to start in 2024. IAEA Director General Rafael Mariano Grossi visited Onkalo in November 2020. (Photo: TVO/Tapani Karjanlahti)

In the United Kingdom, the Nuclear Decommissioning Authority (NDA) published a draft strategy for radioactive waste management, decommissioning and environmental remediation across legacy sites. Over 12 weeks of public consultations, all stakeholders were invited to provide comments, questions and feedback on the draft. The NDA also announced the creation of a working group in Copeland, Cumbria, to discuss geological disposal facility developments and opportunities with local communities, as a first step in a multi-year, consentbased siting process. In addition, construction started on a flexible facility at Tradebe Inutec's Winfrith site to treat low level waste and borderline intermediate level waste.

Switzerland's National Cooperative for the Disposal of Radioactive Waste (Nagra) recommended the construction of a spent fuel encapsulation plant at either the country's future national repository or the ZWILAG Würenlingen Interim Storage Facility (ZWILAG) (Figure C-5).

FIG. C-5. The cask storage hall at ZWILAG in Switzerland is used to store vitrified high level waste from reprocessing plants and spent fuel elements from Swiss NPPs. (Photo: ZWILAG)

In the United States of America, the DOE approved the start of operations for a salt waste processing facility at the Savannah River site for processing high activity liquid waste stored in tanks.

In the first step of its national site selection process, Germany published a list of areas potentially suitable for a disposal site for high level waste. The list and screening process, developed by the Federal Company for Radioactive Waste Disposal, identified 90 areas covering 54% of the country's surface as potentially geologically suitable, as per the site selection criteria and the science-based approach prescribed in a German law from 2017.

The Nuclear Waste Management Organization of Japan initiated a literature survey in two municipalities located in Hokkaido, Suttu town and Kamoenai village, to assess whether they may have a site that is potentially suitable for a deep geological repository, as the first step in the process for siting such a facility. Suttu town made the decision to apply for the literature survey and Kamoenai village accepted the proposal of the survey from the national Government.

Canada's Nuclear Waste Management Organization secured just over 600 hectares of land to conduct its studies in the municipality of South Bruce, Ontario, one of two potential host communities in its site selection process for a deep geological repository for Canada's used nuclear fuel. The federal Government also launched an inclusive engagement process to modernize Canada's radioactive waste policy.

Trends

There has been increasingly focused international cooperation on research, development and demonstration (RD&D) on topics relevant to radioactive waste management. Progress in a significant number of European Union countries has been driven by their obligation to comply with the Waste Framework Directive.

The Implementing Geological Disposal of Radioactive Waste Technology Platform, a self-funded consortium of radioactive waste management organizations cooperating on RD&D topics of shared interest, released its updated Strategic Research Agenda with a focus on efficiency and industrialization of future deep geological repository implementation, as well as on the development of additional concepts viable for smaller inventories.

The European Joint Programme on Radioactive Waste Management (EURAD) presented its comprehensive road map to interested end users. The road map provides a structured approach towards endpoints for radioactive waste management, including gap analysis and further RD&D needs, strategic studies with an emphasis on small inventories management, and knowledge management, as well as highlighting the importance of training and transfer of knowledge.

The European Union launched the PREDIS (Pre-Disposal Management of Radioactive Waste) project, which focuses on the RD&D needed in predisposal treatment and conditioning of radioactive waste streams other than nuclear fuel and high level radioactive waste.

The European Repository Development Organisation (ERDO) Working Group launched a cooperation project involving Croatia, Denmark, the Netherlands, Norway and Slovenia to coordinate efforts in assessing the viability of borehole disposal for high level waste inventories.

The growing number of success stories is an enabling trend for waste management. In Sweden, the municipal council of Östhammar voted in favour of the planned repository for spent nuclear fuel at Forsmark (Figure C-6), to be constructed by Swedish Nuclear Fuel and Waste Management Company (SKB). The final decision to authorize the project rests with the Swedish government.

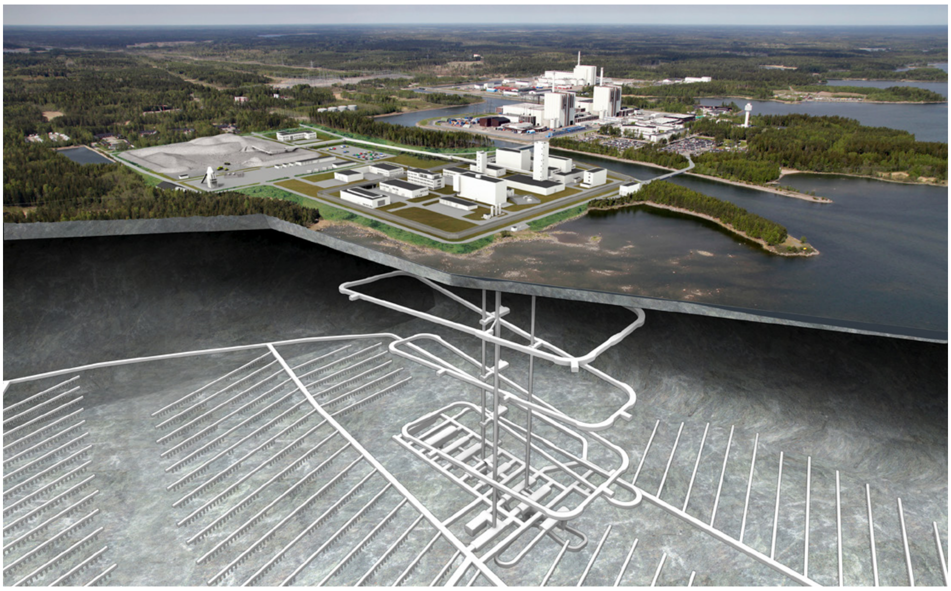
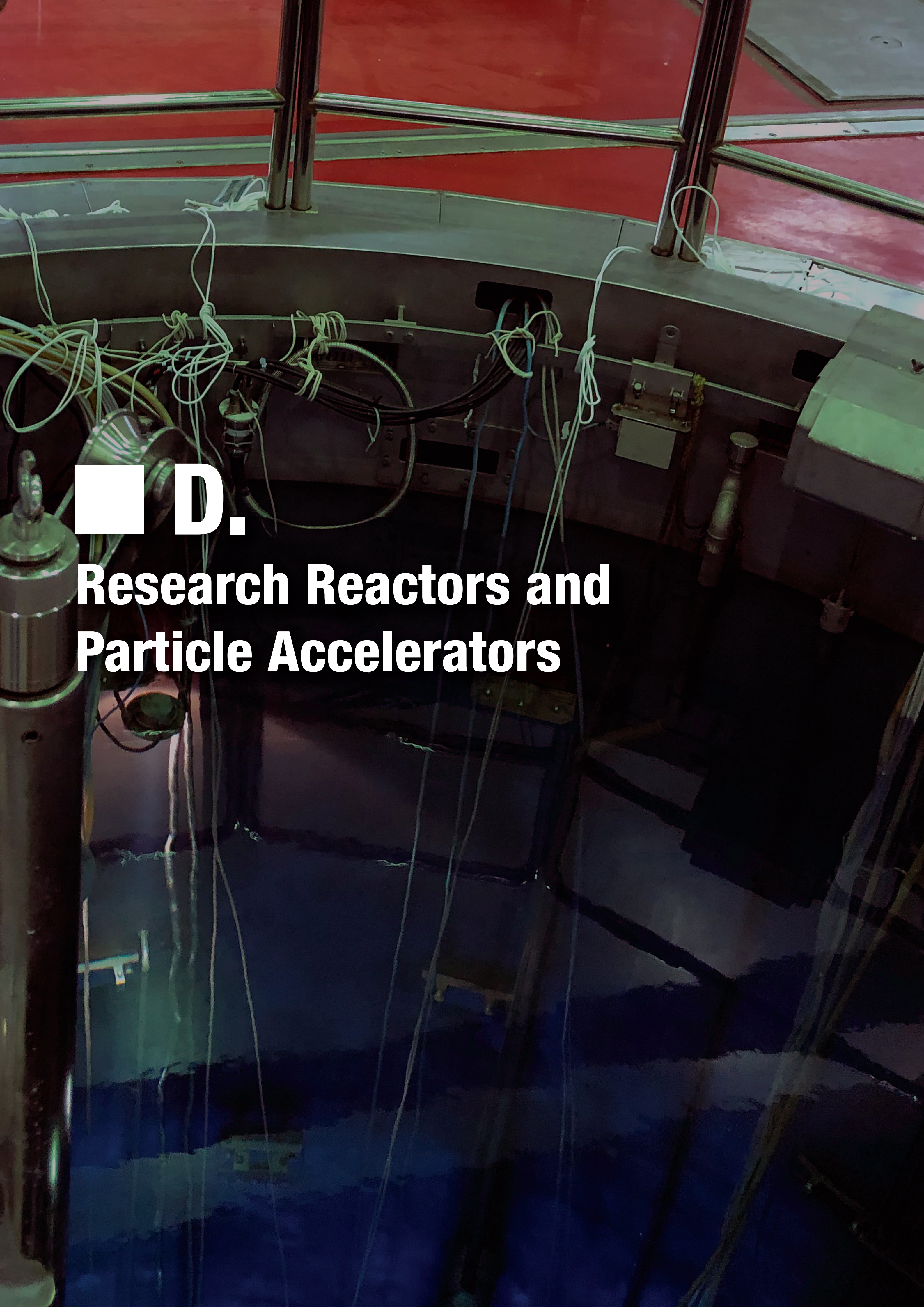


FIG. C-6. An artist's rendering of the underground disposal facility in Forsmark. (Source: SKB)

In France, an activated waste conditioning and storage facility, ICEDA, received a licence to operate, allowing Électricité de France to condition and store radioactive waste in preparation for its future disposal in the country's comprehensive suite of disposal solutions.

Some 42 Member States nominated a Country Coordinator for the Spent Fuel and Radioactive Waste Information System, while 83 Member States were Contracting Parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management by the end of 2020.

D. Research Reactors and Particle Accelerators



D. Research Reactors and Particle Accelerators

D.1. Research Reactors

Status

During the COVID-19 pandemic, research reactors producing medical radioisotopes for global supply were declared as providing essential services to minimize the effect of pandemic related restrictions. All reactor operating organizations introduced proactive measures to ensure safety of facilities and personnel during the pandemic. Some research institutions and universities that operate research reactors for education, training and research temporarily shut down their facilities and maintained them in a safe shutdown state. The transportation of radioisotopes became challenging amid the COVID-19 restrictions, as shown in the Agency's survey of major reactor-based medical radioisotope producers, which assessed the impact of the pandemic on the continuity of the supply chain. The Secretariat organized an informal technical briefing for Member States on the production of radioisotopes in research reactors, as well as on using medical cyclotrons, the transportation and production of radiopharmaceuticals, and demand for radiopharmaceuticals during the COVID-19 pandemic.

Eleven new research reactors are under construction in eight countries: Argentina, Brazil, France, India, the Republic of Korea, the Russian Federation, Saudi Arabia and Ukraine (an accelerator driven system). Several Member States had formal plans to construct new ones, including Bangladesh, Belarus, Belgium, Bolivia, China, the Netherlands, Nigeria, Tajikistan (completion of the Argus-FTI reactor), Thailand, the United States of America, Viet Nam and Zambia. Others, such as Azerbaijan, Ethiopia, Ghana, Kenya, Malaysia, Mongolia, Myanmar, the Niger, the Philippines, Senegal, South Africa, Sudan, Tunisia and the United Republic of Tanzania, are considering building new facilities.

Research reactors remained indispensable for providing radioisotopes for medicine and industry, neutron beams for materials research and non-destructive testing, analytical and irradiation services for both the private and the public sectors, and services for cultural heritage and environmental studies. They make a strategic contribution to education and training (Figure D-1). The most frequent applications for research reactors are shown in Table D-1 in the Annex.

FIG. D-1. Research reactors have a range of uses, from training and education to applications in industry, medicine and more. (Photo: IAEA)

While digital neutron imaging is normally conducted using high intensity neutron sources, standard neutron imaging, such as radiography and computed tomography (CT), can now also be performed using lower intensity neutron sources, with in-core fluxes of around 10^{12} $s^{-1}cm^{-2}$. This was made possible thanks to recent progress in astronomy cameras that have led to the development of comparatively simple low-cost digital neutron imaging systems. The image quality is competitive for standard applications and is sufficient for about 80% of all imaging applications (Figure D-2). This development will allow the expansion of nuclear imaging towards the use of lower intensity neutron sources, both research reactor- or accelerator-based. In 2020, the Agency launched an e-learning course on neutron imaging, which covers this expansion.

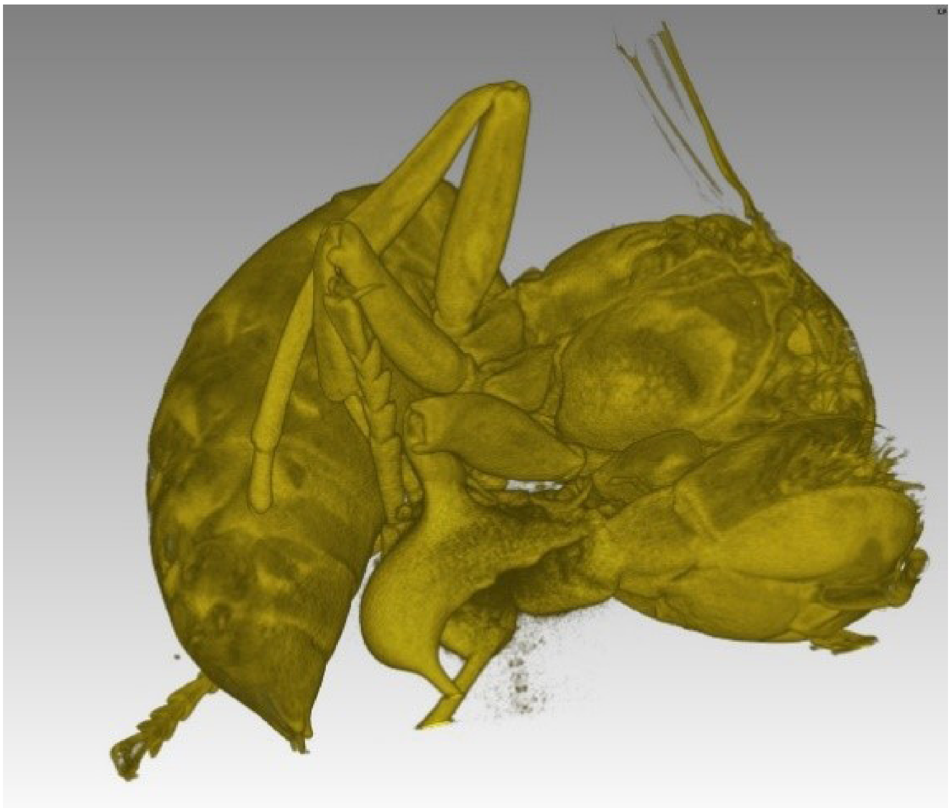


FIG. D-2. High-resolution 3D CT image of a hornet. (Photo: Burkhard Schillinger, Technische Universität München, Germany)

To date, 107 research reactors and four medical isotope production facilities have been converted from the use of high enriched uranium (HEU) to LEU or confirmed as being shut down. In 2020, Kazakhstan eliminated its last remaining unirradiated HEU by down-blending it to below 20% enrichment, and continued preparations for the removal and disposition of irradiated HEU fuel. In total, international programmes have completed the removal or confirmed disposition of approximately 6815 kg of HEU of Chinese, Russian, US and other origin.

International efforts continued to transition medical isotope producers from the use of HEU to LEU targets. The National Institute for Radioelements in Belgium started commercial supply of molybdenum-99 produced with LEU, joining other global leaders in the production of this highly demanded radioisotope for medicine, with a plan to further increase its non-HEU Mo-99 production and achieve full conversion by 2022.

Trends

Global interest in research reactors continued to grow. Many countries take advantage of opportunities to access existing research reactors, including through the Agency's regional research reactor schools for capacity building and through the IAEA-designated International Centre based on Research Reactor (ICERR) scheme. In 2020, the Institute for Nuclear Research, based in Pitesti, Romania, was newly designated, while the French Alternative Energies and Atomic Energy Commission was re-designated for a period of five years. The use of e-learning and capacity building tools, such as the Agency's Internet Reactor Laboratory, gained in importance, with increased interest and support from both the Secretariat and Member States.

More than 60% of the world's operating research reactors are over 40 years old. Their life cycle can attain or go beyond 60 years, but it is of paramount importance that adequate ageing management, refurbishment and modernization programmes be established in time. In view of the general trend towards reductions in funding for such facilities and limited succession planning, sound management systems, operation and maintenance, and life management programmes are vital so that research reactors can fulfil their mission in a cost-effective manner.

D.2. Particle Accelerators and Instrumentation

Status

In the past decade, there has been growing interest from many Member States in developing Compact Accelerator-based Neutron Sources (CANS) as an alternative to the ageing fleet of low and medium power research reactors, with more than 50 such projects in progress in about 20 countries worldwide. CANS encompass many classes of accelerators whose purpose is to offer neutron fluxes in the range of 10^{11}-10^{13} s^{-1} cm^{-2} for a variety of applications. In 2020, the Helmholtz Centre Jülich in Germany finalized a conceptual design for a CANS device based on a high current proton linear accelerator (linac) to serve as a national neutron scattering facility. Such a relatively inexpensive and light infrastructure demanding compact neutron source would be capable of serving a number of instruments for analytical purposes and would be suitable for universities as well as private industries, which could make neutron beam techniques more widely available and applicable.

Another example of a high intensity new superconducting linac and its experimental halls, is illustrated in Figure D-3. This facility, named SPIRAL2, currently being commissioned and located at the National Large Heavy Ion Accelerator (GANIL) research centre in France, will probe short lived heavy nuclei and address applications in fission and fusion as well as materials science using charged particle and neutron beams. Light ion beams from the linac, including alpha particles and lithium-6 or lithium-7 impinging on lead and bismuth targets, will also be used to investigate more efficient methods for the production of certain radioisotopes for cancer therapy.

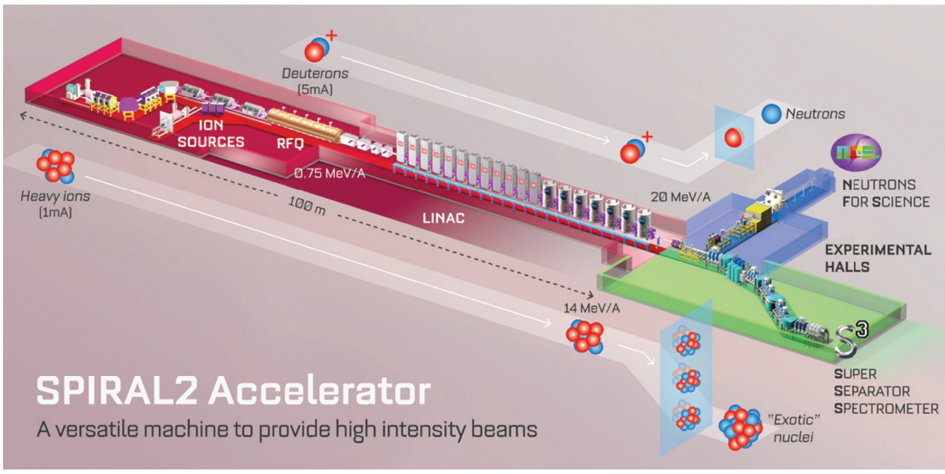


FIG. D-3. The SPIRAL2 facility, based on a superconducting high-power (200 kW) linac. The Neutrons for Science beam line will offer unprecedented neutron beam intensities in the energy range between 1 and 40 MeV — up to two orders of magnitude higher when compared to other similar installations. (Image: Alahari Navin, GANIL, France)

Figure D-4 illustrates another project using a superconducting high-power (200 kW) linear proton/deuteron accelerator entering phase 2, i.e. an increase in energy from 5 to 40 MeV with an expected neutron source intensity of up to 10^{15} n/s for diverse applications, including basic research with neutrons.

FIG. D-4. The superconducting high-power (200 kW) linear proton/deuteron accelerator (left), combined with innovative liquid lithium target technology for neutron production (right). (Image: Dan Berkowitz, Soreq Nuclear Research Center, Israel)

Finland, through the Helsinki University Hospital, is at the end of its commissioning phase of a compact proton accelerator (a 2.6 MV electrostatic accelerator designed to operate at 30 mA) based neutron source in the hospital environment, with the main objective of starting boron neutron capture therapy trials and later moving on to patient treatment. The neutrons are produced on a rotating lithium target.

A notable development was made in the field of radiation sensors for application in unmanned aerial vehicle (UAVs). Gamma spectrometric systems based on scintillator detectors, such as lanthanum (III) bromide ($LaBr_3$) or cerium (III) bromide ($CeBr_3$) detectors, are increasingly preferred over simple Geiger–Müller counters. One recent success in radiation detection for UAV radiological mapping was the commercial availability of scintillation detectors based on silicon photomultipliers and enhanced with built-in temperature compensated bias generator and preamplifier. This allows for fast digital signal processing of the detector signal and processes all measured data in real time with accurate global navigation satellite systems GNSSs georeferencing to produce high-resolution mapping (Figure D-5) of radiation levels and identification of radioisotopes.

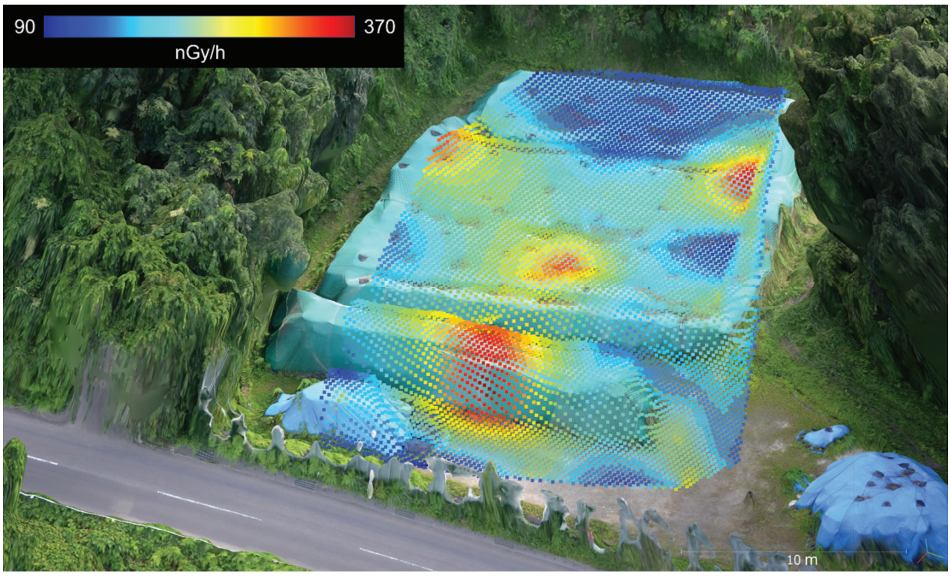


FIG. D-5. High-resolution radiological map (red indicates elevated dose rates) combined with 3D aerial photogrammetry. The map was obtained using a single UAV in two consecutive flights. (Image: IAEA)

Trends

Developments in the field of radiation monitoring systems based on the UAV/drone platform are accelerating mainly due to the expansion of UAV technology and the design of miniaturized radiation detectors, combined with GNSSs and fast data processing algorithms. The growing demand for flexibility and operability of mobile monitoring systems means prioritizing UAV-based solutions for hazardous areas or those inaccessible by persons for radiological mapping, for search of radiation sources as well as for rapid emergency response following radiation incidents or accidents. The UAVs are becoming more rugged robust in terms of withstanding operating conditions such as temperature and humidity, and water and /dust resistance. In addition, their autonomy is increasing thanks to better options for prolonged flight time, environment sensing, advanced mapping capabilities as well as data processing algorithms improved by the use of artificial intelligence.

Machine learning based approaches have great potential to advance nuclear science and applications in a number of domains, such as cancer staging in nuclear medicine and cancer treatment through radiotherapy; to accelerate progress in nuclear fusion research and to help protect the environment, in particular global water resources, from overexploitation and contamination. Very recent and multiple instances have demonstrated the power of forensic intelligence to provide technological solutions to combat crime in different countries. Trace evidence analysis is a key part of forensic investigations. Machine learning algorithms are being increasingly applied in forensic science to help solve challenges that were previously unsolved. Machine learning methods can also be used as a tool to identify patterns and classify various samples, providing a valuable means of meeting such challenges.

For example, in the forensic analysis of glass, samples are typically compared using their elemental intensity ratios. If large enough, broken glass fragments can be traced to their original shape and origin by forensics practitioners. For small fragments, however, this task is impossible with traditional methods. In such cases, nuclear analytical techniques such as particle induced X-ray emission and neutron activation analysis, when combined with machine learning tools and glass-specific fabrication databases (inventory), can be used to match the suspect to a crime scene (Figure D-6).

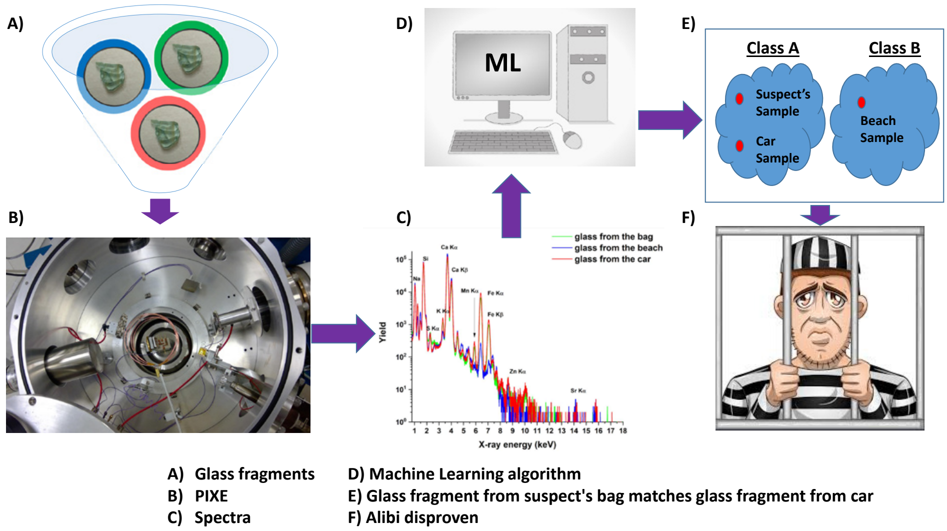


FIG. D-6. Machine Learning based workflow. Initially, samples are gathered from crime scene (A) and sent for Elemental Analysis using PIXE (B). The resulted measurements are analysed and (C) passed on to machine learning models (D) that produce classification for the samples (E). With this knowledge, police investigators can confirm or disprove an alibi. (E) demonstrated that in the hit-and-run case, the fragment that was found on the suspect and the fragment from the hitting car were both classified as the same class and the fragment from the beach was classified differently, thus suggesting that the suspect and the hitting car are linked. (Image: Bar-Ilan University and its Institute for Nanotechnology and Advanced Materials, Israel)

E.

Food and Agriculture

E. Food and Agriculture

E.1. Radiolabelled Approaches and Innovative Nuclear Techniques for Measuring Residues in Food — Addressing Public Health and Trade Needs

Status

During food production worldwide, chemicals such as veterinary drugs and pesticides, including herbicides, are used. However, remnants of chemicals in food present public health and trade concerns and must consequently be regulated using standards referred to as maximum residue limits (MRLs), which set out the highest concentrations of residues allowed in/on food. MRLs impact trade, and those established by the Codex Alimentarius Commission are referenced by the World Trade Organization Agreement on the Application of Sanitary and Phytosanitary Measures. Harmonized MRLs benefit governments, farmers, traders and the public. Trade is significantly disrupted when MRLs are missing . There are several compounds used in food production for which MRLs are currently missing.

To determine MRLs for veterinary drugs, and therefore fill the gap in food standards, information from animal metabolism (residue depletion) studies involving the use of radiolabelled material is required. Nuclear techniques, among others, can enable the traceability and accurate measurements required in metabolism studies.

The drugs or related compounds radiolabelled with isotopes such as carbon-14, sulphur-35, phosphorus-32 and hydrogen-3 are administered in targeted food animals and used to track their distribution and breakdown into residues and key metabolites, especially in edible tissues (e.g. muscle, liver, kidney and fat). Radiolabelled studies, considered to be the 'gold standard' of metabolism studies, are used in the human and veterinary pharmaceuticals and agrochemicals sectors, generating data to facilitate safety evaluation, therefore ultimately protecting consumers. The determination of radioactivity levels currently involves combustion and solubilization of animal tissue, which require reliable accurate measuring techniques to confirm the type and concentration of residues.

Trends

The use of chemicals in food production is changing around the world. Each year, drugs/chemicals are developed to address new challenges. The demand for regulating these chemicals, requiring radiolabelled studies for which there is no alternative technique, has thus increased. Radiolabelled compounds play a crucial role, as they allow for the tracing and studying of all chemical residues through the various tissues.

Tools and techniques such as hydrogen-3 and carbon-13 nuclear magnetic resonance, liquid scintillation counting and radio-receptor/-immuno assays are required to analyse and characterize radiolabelled compounds in animal tissues during metabolism studies. Generating accurate data also requires innovative and cost-effective nuclear analytical techniques/methods such as competitive radio receptor assay, among others, supported by high resolution mass spectrometry. New technologies in autoradiography are also emerging as an additional investigative tool, facilitating quantitation and visualization of radioactivity in intact tissue and organs.

Recent reports indicate that veterinary drugs in food-producing animals may also result in some residues that are not easily extracted from the tissues and are therefore not detected during laboratory analysis of food for human consumption. These residues may pose toxicological concerns to consumers. The development of innovative analytical methods to reveal these ‘hidden’ hazards is therefore required.

Another emerging food safety concern, in some regions, is the need for scientific data to facilitate setting of standards and MRLs for food that may be of local and regional significance, such as offal (internal animal organs). These types of food will be the subject of new radiolabelled animal metabolism studies. Currently, when radiolabelled animal studies are conducted, an individual drug and/or chemical is the target for a study, even though combinations of drugs are used in food production. Information generated in single drug use studies is therefore incomplete. Therefore, radiolabelled studies administering chemical combinations will henceforth be conducted.

A related emerging area of interest to which radiolabelled studies can further contribute is the global call for risk managers to harmonize standards and MRLs for compounds used in both animal and plant production, as opposed to the current practice, where standards are set separately for animal and plant products, which does not help provide a clear picture of the hazard levels in the foods consumed.

There is an increasing interest in developing countries in participating in radiolabelled animal studies and producing scientific data for setting standards, given the impact of missing MRLs on these countries’ economies and consumer needs. In this regard, the Agency has recently initiated a new coordinated research project (CRP), on depletion of veterinary pharmaceuticals and related substances used in animal production, attracting interest from several Member States. The research being planned involves animal species such as cattle, equines, fish, goats and sheep (Figure E-1), with the potential for extension to certain crops, especially in relation to feed contamination. The CRP is expected to contribute to reducing the dependence of developing countries on external facilities and institutions in conducting radiolabelled studies for risk assessment data generation and MRL setting to facilitate trade and protect consumers.

FIG. E-1. Some of the target animals for radiolabelled depletion studies in Sudan. (Photo: IAEA)

F.
Human Health

F.
Human Health

F.1.
Advances in Microdosimetry and Nanodosimetry

Status

Microdosimetry is the subfield of radiation physics involving the systematic study of the spatial distribution of the absorbed energy in microscopic structures within irradiated matter. Although it originated more than 60 years ago, microdosimetry is still attracting significant scientific interest in radiation medicine, radiation protection, radiation biology and other fields such as space research.

In the field of radiation medicine, microdosimetry is particularly relevant for ion beam therapy, an advanced technique that uses proton and carbon beams instead of the conventional photon irradiation, to treat tumours, minimizing the damage to healthy tissue. In this application, the standard measurement of the absorbed dose is not sufficient to explain the outcomes of the radiation, as the radiobiological effectiveness varies along the path of a clinical ion beam in the human body.

In radiation protection and in a number of modalities in radiation medicine, therefore, macroscopic weighting factors are applied to the absorbed dose in order to account for the biological effectiveness of the particular radiation quality (relative numbers of particles according to type and energy at the locations of interest in the target material). Examples include proton and ion beams, neutrons, and kilovolt X-rays as used in brachytherapy. Microdosimetry and nanodosimetry (also known as structural microdosimetry) provide radiation quantities that capture the influence of the nature of radiation interactions and, hence, the properties of different radiation qualities responsible for their biological effectiveness.

Microdosimetry is a wide, interdisciplinary field. It ranges from simulations and modelling, to development of dedicated detectors and instrumentation, and clinical and other applications.

There is no single microdosimeter capable of characterizing appropriately all different ionizing radiations, and recent studies worldwide are focused on detectors developed for specific applications. For the intense ion beam currents used in therapy applications, the goal is to reduce the detector to submillimetre sizes, while, for radiation protection and space purposes, large-area microdosimeters are developed.

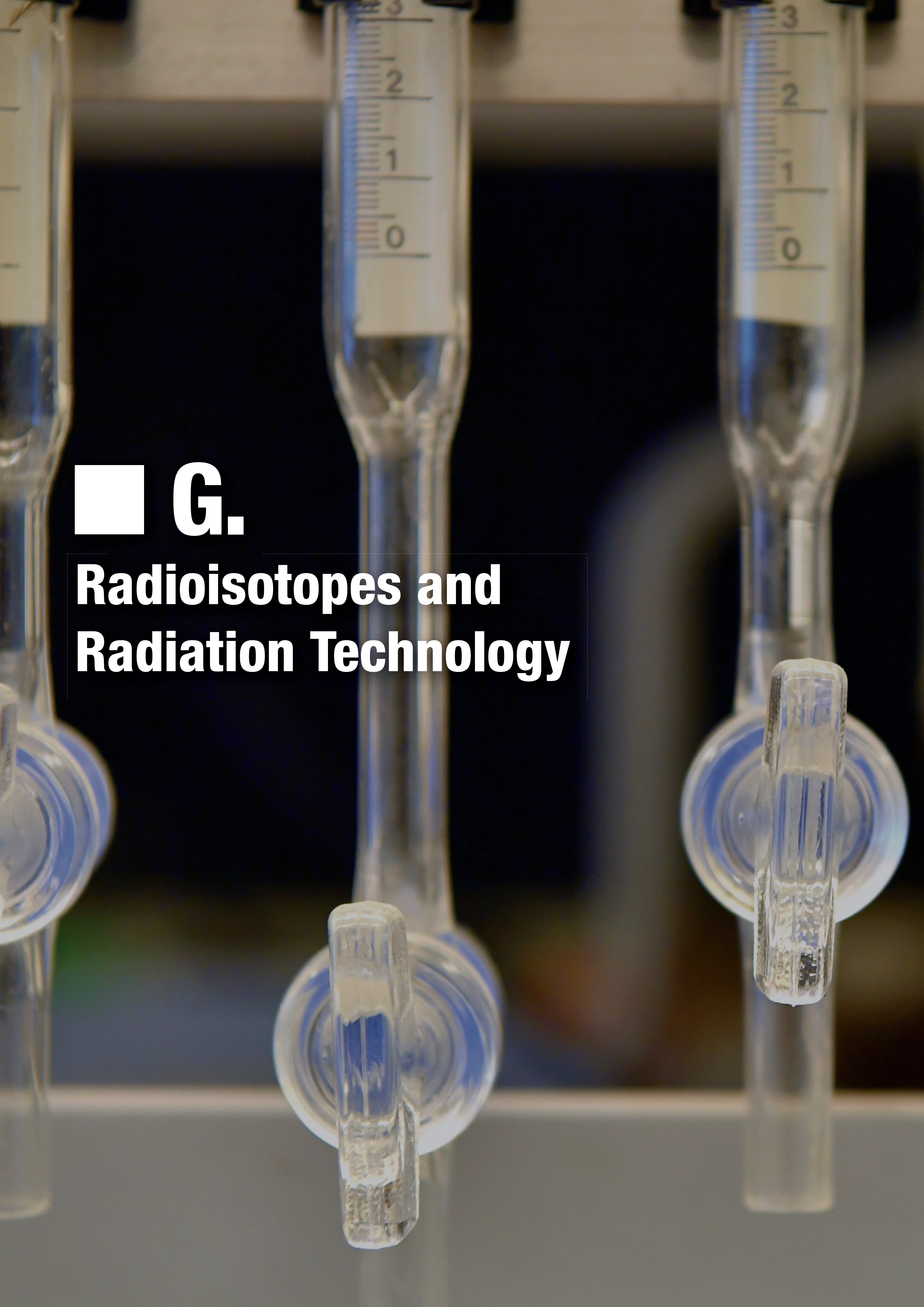
Trends

A number of issues still need to be resolved before microdosimetry can become a standard for estimating biological effects in different uses of radiation technologies. A fundamental milestone is the standardization of microdosimetric data, which include a study of the uncertainties budget.

A first step consists of the development of shared methodologies and mechanisms for reporting microdosimetry. Efforts are still needed to compare microdosimeters that are different in sensitive volume, shape and material to obtain univocal and detector-independent results. Furthermore, the microdosimetric data should be investigated to predict the parameters adopted for the specific use of the detectors: the linear energy transfer in ion beam therapy (Figure F-1), the relative biological effectiveness in radiobiology, and the quality factor in radiation protection.

FIG. F-1. Ion beam therapy planning and implementation is one of the areas in which microdosimetry could provide a valuable contribution. The figure shows an irradiation room of MedAustron ion beam therapy centre in Wiener Neustadt, Austria, where tumour patients are treated with proton and carbon ion beams. The ceiling-mounted robotic arm holds the patient couch and the X-ray imaging ring is used for patient alignment. (Source: MedAustron, Austria. Author: Kästenbauer/Ettl.)

The Agency can play a strategic role in providing the multidisciplinary expertise and environment required in this area. Directions for future research were identified during the Technical Meeting on New Trends and Advances in Microdosimetry and its Applications organized by the Agency in October 2020, including major themes such as ion beams, radiation protection aspects, biology modelling and nanodosimetry. Those directions will be used to guide the Agency's related research and development work in the coming programme cycles.



G.

Radioisotopes and Radiation Technology

G. Radioisotopes and Radiation Technology

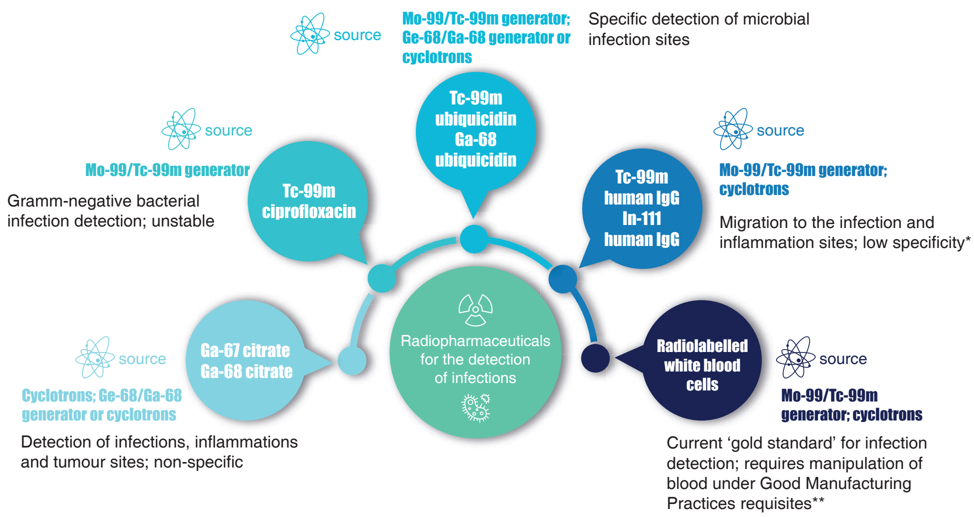
G.1. The Role of Radiopharmaceuticals in the Detection, Diagnosis and Management of Infectious Diseases

Status

Infectious diseases are a threat for the human population, as demonstrated by the current COVID-19 pandemic. While all scientific disciplines are focusing their efforts to better understand such diseases by using advanced technologies, the development of radiopharmaceuticals is at a stage where non-invasive visualization of the cellular and biochemical processes is becoming possible, paving the way for diagnosis and potential therapeutic approaches using radiopharmaceuticals for human infectious diseases.

The importance of early detection and treatment of infectious diseases is a major factor in the control and reduction of patient morbidity and mortality. The immune response to infection is a complex phenomenon, and an ideal radiopharmaceutical should be able to specifically distinguish live infecting organisms from non-pathogens, other infections and inflammation in the body. It should show quantitative accumulation and sufficient retention only in infected tissues, for accurate diagnosis and/or evaluation of treatment response.

Several radiopharmaceuticals play a significant role in the non-invasive detection of infections in clinical settings. However, none of these clearly distinguish the specific cause of infection, or different types of infections.



* *Development of kits for Tc-99m radiopharmaceuticals for infection imaging (IAEATECDOC1414)*

** *Radiolabelled Autologous Cells: Methods and Standardization for Clinical Use (IAEA Human Health Series No. 5)*

Trends

Currently, as the complexity of infections is increasing, including life threatening viral infections in recent decades, such as human immunodeficiency virus (HIV), severe acute respiratory syndrome, avian flu, Ebola and COVID-19 infections, several promising molecules are being identified that can be used to detect and diagnose a specific infection in human bodies or human samples.

For over 20 years, the IAEA, in partnership with the FAO, has trained and equipped experts from all over the world to use nuclear and nuclear derived immunological (e.g. Radio-immuno Assay (RIA), Enzyme Linked Immunosorbent Assay (ELISA)) and molecular (Polymerase Chain Reaction (PCR)) technologies. These sensitive and specific technologies, and their applications, have increasingly been used for the early and rapid detection, characterization, surveillance and control of transboundary animal and zoonotic diseases. Recently, these techniques have been employed to diagnose infectious diseases with pandemic potential such as African Swine Fever, Foot-and-Mouth Disease, Ebola, Zika, Avian Influenza, MERS and SARS, and recently COVID-19. The Agency laboratories at Seibersdorf provided expert guidance and services, standard operating procedures (SOPs), personal protective equipment (PPE) training as well as technical capacity building and test procedure training together with the Agency's COVID-19 support package of equipment/reagents/consumable to more than 120 Member States.

Monoclonal antibodies (MAbs), which can be produced on a large scale in specialized laboratories, have evolved since their discovery in 1973 and can now be used for new macromolecular biological therapeutics. MAbs used for tumour treatment can attach to tumour-specific antigens and are used as vehicles to deliver radionuclides to a specific tumour site. This new technique emerged in the use of radiolabelled MAbs containing photon emitting radioisotopes, which, after injection into the human body, can be used for diagnosis of cancers. This is known as radioimmunoscintigraphy (RIS).

In the next step, scientists prepared radiolabelled MAbs containing beta emitting radioisotopes that could identify and target tumour cells to bombard tumour cells with high-energy beta particles in order to destroy the cancerous cells. This is known as radioimmunotherapy (RIT).

It was found that foreign microbial surface molecules can trigger the production of microorganism-specific MAbs in a host, therefore allowing the use of RIS and RIT for the detection of a variety of infectious diseases, including fungal, viral or bacterial threats, and potential application in therapy. Clinical trial databases show at least 88 studies in clinical trials for the use of MAbs on COVID-19 patients. Preliminary studies also explore the use of RIS to diagnose COVID-19, based on specific viral surface antigens. One example involves the use of recombinant antibody 'Anti-SARS-CoV-2 Spike Glycoprotein S1' (CR3022), which was developed at commercial scale initially for ex vivo tests, such as enzyme-linked immunosorbent assays, and is now considered an agent that could potentially be used in the diagnosis of COVID-19 (Figure G-1). The MAb has successfully been labelled with iodine-131 for binding studies and as a proof-of-concept test, and is proposed for application as a therapeutic radiolabelled version of CR3022.

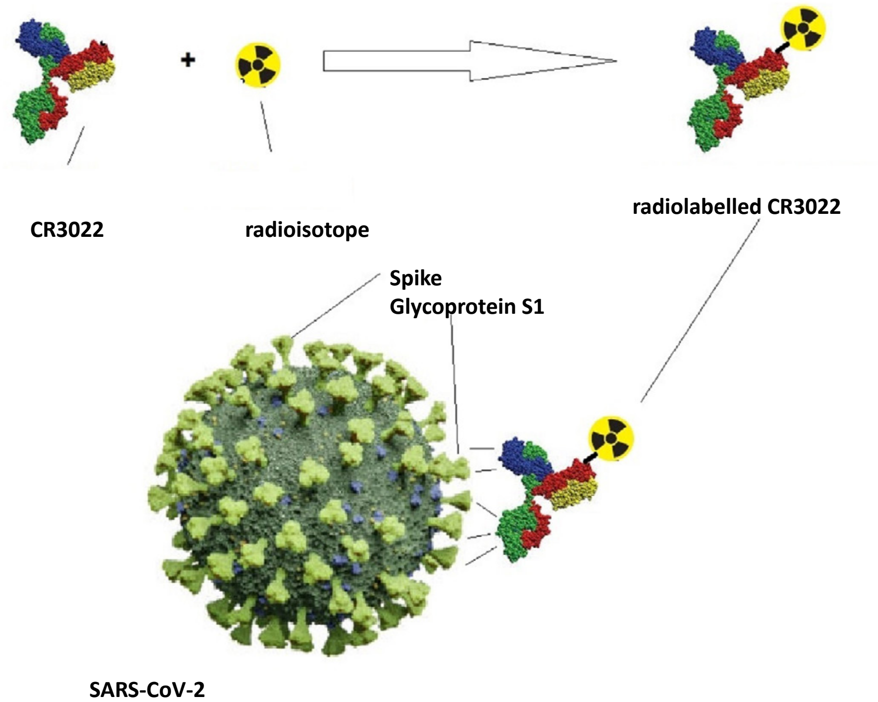


FIG. G-1. The schematic potential development of theranostic radiolabelled CR3022 monoclonal antibody against severe acute respiratory syndrome coronavirus 2 (SARSCoV2) for diagnosis purposes (Source: IAEA)

However, many questions remain unanswered, such as how mutations in the virus genome would affect the effectiveness of the method.

According to a study, the therapeutic radiopharmaceutical Bi-213 anti-HIV-1 gp41 successfully eliminated HIV-infected peripheral blood mononuclear cells and monocytes without damage to the blood brain barrier in humans, potentially paving the way to treat HIV infections.

These encouraging recent developments related to novel radiopharmaceuticals prepared using microorganism-specific MAbs, demonstrate the potential for diagnosis and treatment of infection diseases, and exploring their use is both relevant and timely for all Member States.

■ H.
Environment

H. Environment

H.1. Nuclear and Derived Techniques to Advance Knowledge of Global Blue Carbon and Address Climate Change Impacts

Status

The dramatic rise in atmospheric GHGs, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), since the late 19th century, has led to increased global warming, with CO_2 emissions from fossil fuel combustion, cement production and anthropogenic or land use change being the main contributors. The ocean plays a major role in regulating the global climate system by capturing and storing CO_2 away from the atmosphere, i.e. acting as a net sink for anthropogenic CO_2 and very significantly reducing the rate of global warming.

Two of the main mechanisms by which the ocean captures CO_2 from the atmosphere are the solubility pump (absorption of CO_2 by gas exchange and downward transfer of CO_2-enriched water to the deep ocean) and the biological pump (vertical export of photosynthetically produced particulate organic carbon from surface water to the deep ocean).

Trends

The organic carbon (OC) captured and stored by the ocean is known as blue carbon. Vegetated coastal ecosystems, such as seagrass meadows, tidal marshes and mangrove forests, accumulate and store large stocks of OC in their sediment. Although the total global area of these ecosystems is much smaller than that of terrestrial forest ecosystems, their global OC sequestration potential is substantial, which means they should be a major consideration in global nature-based climate change adaptation strategies (Figure H-1). These same sediment records that have been age dated using short lived radioisotopes can be also mined for legacy plastic pollution (Figure H-2). The IAEA Environment Laboratories develop geochronological models extracted from sediment cores that are collected in coastal mangrove environments using, for example, excess 210Pb, 7Be, 234Th, and 137Cs as short lived radiotracers.

FIG. H-1. Global distribution of blue carbon coastal ecosystems. (Adapted from https://thebluecarboninitiative.org)

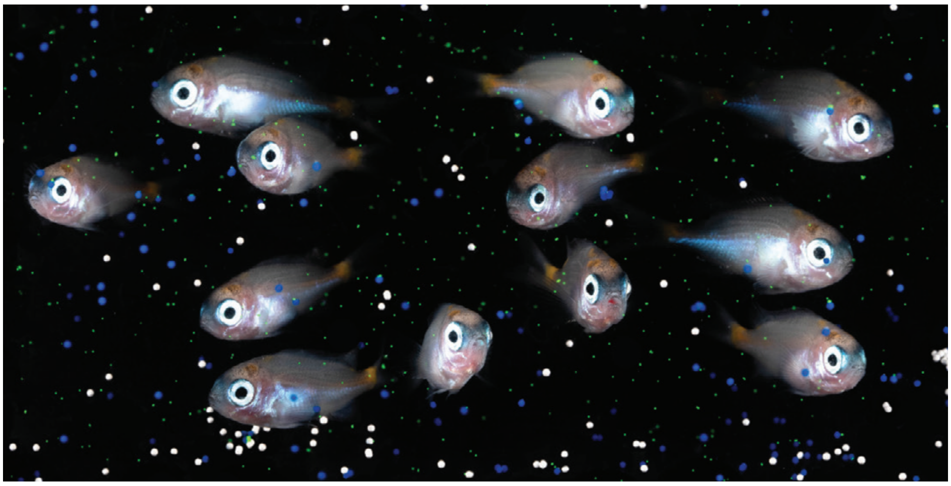


FIG. H-2. Fish exposed to microplastics as part of the R&D undertaken in the IAEA Environment Laboratories in Monaco. (Photo: IAEA)

In addition, the current magnitude of sedimentary carbon losses resulting from widespread habitat degradation necessitates coordinated actions directed at habitat creation and restoration, as well as implementation of creative eco-engineering solutions.

The inclusion of coastal blue carbon ecosystems in existing mitigation strategies, through carbon sequestration and GHG offsets, requires the quantification of accurate accumulation rates of OC sequestration, which at present is limited and subject to large uncertainties. Determination of OC sequestration at millennial timescales can be done using carbon-14, while estimates at decadal/centennial timescales can be achieved using radionuclides that are present in the environment, such as lead-210, caesium-137 and plutonium isotopes. This provides a timeframe compatible with management actions within the United Nations Sustainable Development Goals and the United Nations Decade of Ocean Science for Sustainable Development framework, enabling the determination of OC sequestration and its variation over time due to natural and human alterations.

Radionuclides can also provide a unique assessment of whether natural or anthropogenic disturbances may have caused losses of carbon, for instance via sediment resuspension and erosion processes. The use of shorter-lived radionuclides, such as thorium-228, thorium-234 and beryllium-7, as tracers of sedimentation dynamics at timescales of weeks, months or even a few years, would be compatible with the establishment of blue carbon policy frameworks that support the quantification and financing of carbon emission reductions.

While a number of studies have been conducted on blue carbon in coastal vegetated areas during the last decade (Figure H-3), many questions remain unanswered. These questions encompass aspects such as the evaluation of global hotspots that are largely understudied (e.g. seagrasses and mangroves in Brazil and Asia); how climate change and other disturbances will impact blue carbon in coastal vegetated systems; the role of macroalgae; and the best management actions for maintaining and enhancing carbon sequestration in coastal blue carbon habitats. Nuclear and derived techniques are instrumental in the assessment of the role of carbonate and macroalgae in the carbon cycle, the determination of carbon provenance, understanding factors that influence sequestration in blue carbon habitats and their corresponding budgets, and management actions to promote blue carbon strategies.

FIG. H-3. Sediment cores collected off Zanzibar, United Republic of Tanzania, to assess inventories and burial rates of organic carbon as a measure of carbon sequestration potential. (Photo: Gloria Salgado, Edith Cowan University, Perth, Australia)

The Agency aims to study several aspects of blue carbon science and transfer the relevant nuclear technologies during the next decade. Through the IAEA Environment Laboratories, the Agency is currently involved in blue carbon projects in Australia, Brazil, Denmark, France, India, Myanmar, New Zealand, the United Republic of Tanzania and the United States of America. The Agency is also engaged in an innovative project coordinated by Oceans 2050 to assess the carbon sequestration capacity of seaweed farms across the world. National and regional technical cooperation projects are being developed to assess the importance of carbon sequestration in aquatic systems for nature-based climate change adaptation strategies, environmental conservation and socio-economic benefits.

■ Annex

Table A-1. Nuclear power reactors in operation and under construction in the world (as of 31 December 2020)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2020		Total Operating Experience through 2020	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	3	1641	1	25	10.0	7.5	91	2
ARMENIA	1	415			2.6	34.5	46	8
BANGLADESH			2	2160				
BELARUS	1	1110	1	1110	0.3	1.0	0	2
BELGIUM	7	5942			32.8	39.1	310	7
BRAZIL	2	1884	1	1340	13.2	2.1	59	3
BULGARIA	2	2006			15.9	40.8	169	3
CANADA	19	13624			92.2	14.6	788	6
CHINA	50	47528	13	12565	344.7	4.9	418	8
CZECH REPUBLIC	6	3934			28.4	37.3	176	10
FINLAND	4	2794	1	1600	22.4	33.9	167	4
FRANCE	56	61370	1	1630	338.7	70.6	2337	0
GERMANY	6	8113			60.9	11.3	852	7
HUNGARY	4	1902			15.2	48.0	142	2
INDIA	22	6255	7	4824	40.4	3.3	548	11
IRAN, ISLAMIC REPUBLIC OF	1	915	1	974	5.8	1.7	9	4
JAPAN	33	31679	2	2653	43.1	5.1	1932	6
KAZAKHSTAN							25	10
KOREA, REPUBLIC OF	24	23150	4	5360	152.6	29.6	596	2
MEXICO	2	1552			10.9	4.9	57	11
NETHERLANDS	1	482			3.9	3.3	76	0
PAKISTAN	5	1318	2	2028	9.6	7.1	87	5
ROMANIA	2	1300			10.6	19.9	37	11
RUSSIAN FEDERATION	38	28578	3	3459	201.8	20.6	1372	5
SLOVAKIA	4	1837	2	880	14.4	53.1	176	7
SLOVENIA	1	688			6.0	37.8	39	3
SOUTH AFRICA	2	1860			11.6	5.9	72	3
SPAIN	7	7121			55.8	22.2	350	1
SWEDEN	6	6882			47.4	29.8	474	0
SWITZERLAND	4	2960			23.0	32.9	228	11
TURKEY			2	2228	NA	NA		
UKRAINE	15	13107	2	2070	71.5	51.2	533	6
UNITED ARAB EMIRATES	1	1345	3	4035	1.6	1.1	0	5
UNITED KINGDOM	15	8923	2	3260	45.7	14.5	1634	7
UNITED STATES OF AMERICA	94	96553	2	2234	789.9	19.7	4600	10
Total [b,c]:	**442**	**392612**	**52**	**54435**	**2553.2**		**18772**	**10**

[a] Source: Agency's Power Reactor Information System (PRIS) (www.iaea.org/pris) as of 1 June 2021.

[b] The total figures include the following data from Taiwan, China: 4 units, 3844 MW(e) in operation.

[c] The total operating experience also includes shutdown plants in Italy (80 years, 8 months), Kazakhstan (25 years, 10 months), Lithuania (43 years, 6 months) and shutdown and operational plants in Taiwan, China (232 years, 8 months).

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

Type of application [a]	Number of research reactors involved [b]	Number of Member States hosting such facilities
Teaching/training	161	50
Neutron activation analysis	116	49
Radioisotope production	82	41
Neutron radiography	70	37
Material/fuel irradiation	67	26
Neutron scattering	44	28
Geochronology	23	20
Transmutation (silicon doping)	22	15
Transmutation (gemstones)	19	12
Neutron therapy, mainly R&D	15	12
Nuclear data measurement	14	7
Other [c]	117	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 236 research reactors considered (221 operational, 15 temporarily shut down, as of November 2020).

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

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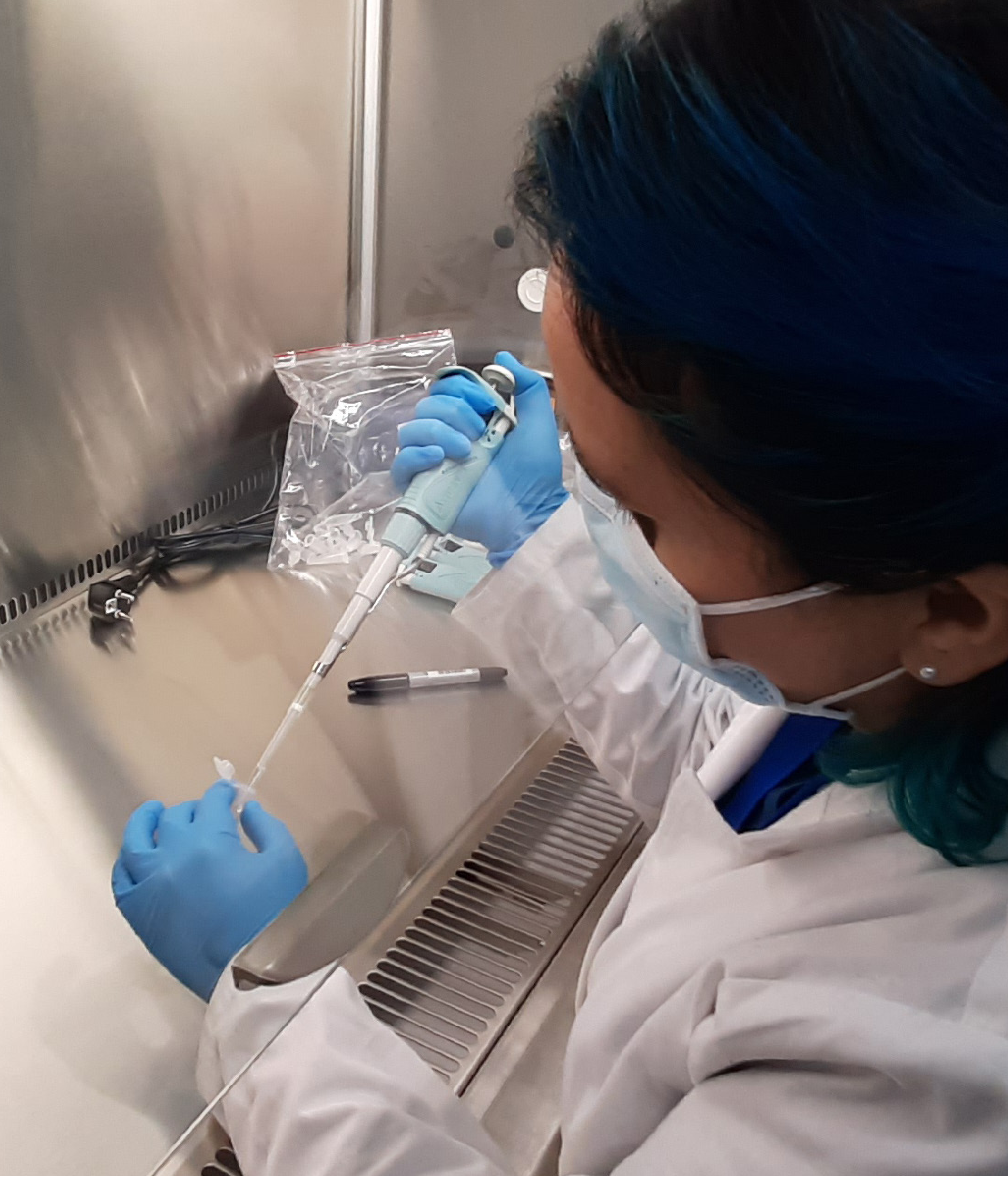

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