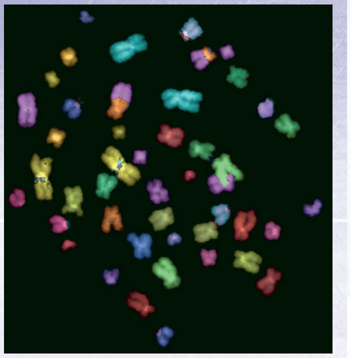
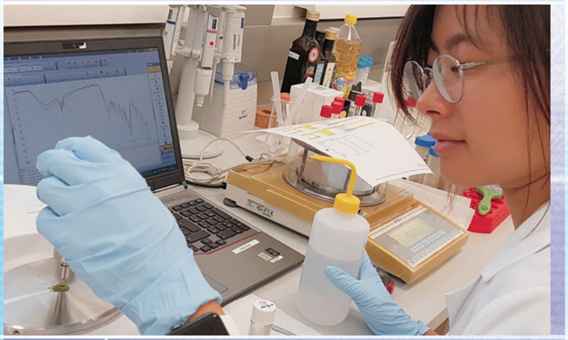
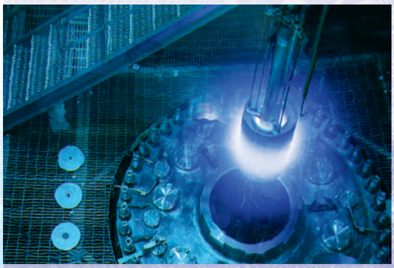
NUCLEAR TECHNOLOGY REVIEW

2020







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Nuclear Technology Review 2020

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Foreword

In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* each year.

The *Nuclear Technology Review 2020* covers the following select areas: power applications, advanced fission and fusion, accelerator and research reactor applications, radioisotopes and radiation technologies, human health and nuclear techniques in food and agriculture.

The draft version was submitted to the March 2020 session of the Board of Governors in document GOV/2020/4. 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.

Table of Contents

Executive Summary

1. At the end of 2019, the 443 operating nuclear power reactors worldwide (Figure A-1) had a total capacity of 392.1 GW(e). In 2019, 13 reactors were permanently shut down, 6 were connected to the grid, and construction started on 5. Near and long term growth prospects remained centred on Asia, home to 35 of the 54 reactors under construction, as well as 61 of the 74 reactors connected to the grid since 2005.

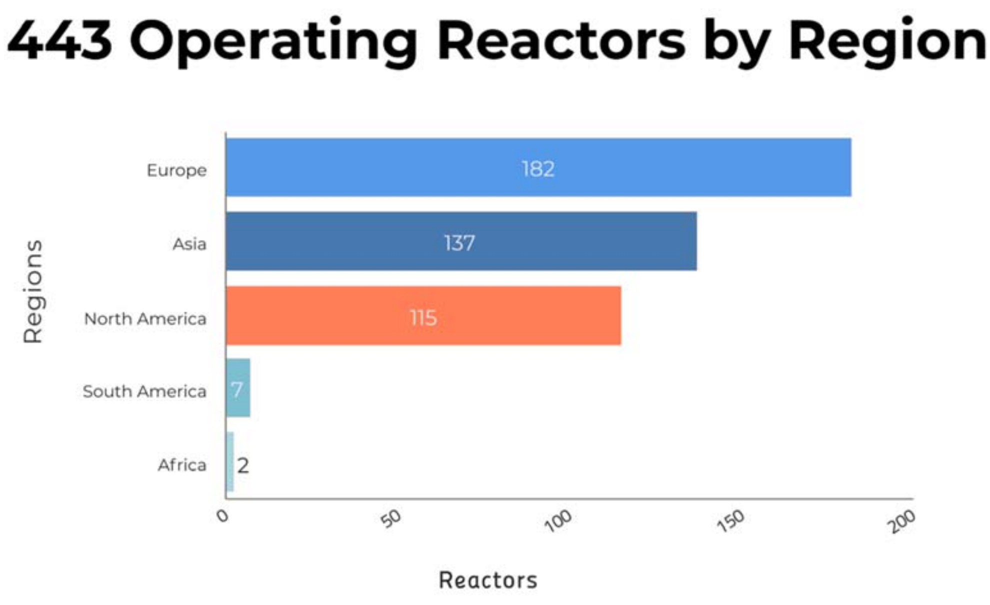


FIG. A-1. Operating nuclear power reactors in 2019. (Source: IAEA Power Reactor Information System www.iaea.org/pris)

2. Thirty countries currently use nuclear power and 28 are considering, planning or actively working to include it in their energy mix. Four newcomer countries are building their first nuclear power plants (NPPs), two of which are near completion, and several others that have decided to introduce nuclear power are at advanced stages of infrastructure preparation.

3. The Agency's 2019 projections for global nuclear power capacity offer a mixed estimate of nuclear power's future contribution to global electricity generation, depending in part on whether significant new capacity can be added to offset potential reactor retirements. In the low projections to 2030, net installed nuclear capacity gradually declines before rebounding to 371 GW(e) by 2050. In the high projections, capacity increases by 25% over current levels to 496 GW(e) by 2030, and by 80% to 715 GW(e) by 2050. Nuclear power's share of the world's total electricity generation will be about 6% in the low case and approximately 12% in the high case by mid-century, compared with about 10% in 2019.

Advantages in terms of climate change mitigation, energy security, and environmental and socio-economic policies are key reasons why many countries intend to introduce or expand their nuclear power programmes. The International Conference on Climate Change and the Role of Nuclear Power, organized by the IAEA in October 2019 in cooperation with the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, stressed that nuclear power has a key role to play in helping to achieve climate goals by accelerating the transition to low carbon energy.

4. World uranium production in 2019 was forecast to be similar to that of 2018 at about 53 500 tonnes. Continued low prices resulted in a significant reduction in uranium exploration, with new uranium projects remaining on hold and a number of previously active mines and processing facilities remaining in a state of care and maintenance. Global conversion, enrichment and fuel fabrication capacities were more than adequate to meet present and projected future demand.

5. In October 2019, the Agency took delivery of a shipment of low enriched uranium (LEU) at a purpose-built facility in Kazakhstan, officially establishing the IAEA LEU Bank, aimed at providing countries with assurance about the supply of nuclear fuel.

6. In the years to come, considerable decommissioning work on power reactors, research reactors, other fuel cycle facilities, critical assemblies, accelerators and irradiation facilities, as well as the related remediation activities, is expected. Both proven and new technologies are delivering continuous improvements in these areas.

7. Several countries progressed in their projects on deep geological disposal of high level radioactive waste and/or spent fuel declared as waste. Finland is constructing a facility, Sweden is awaiting a final decision on its licence application and France is finalizing the licence application for its facility. Borehole disposal projects for disused sealed radioactive sources are progressing in several countries, including the Agency supported pilot projects in Ghana and Malaysia. Disposal facilities for all other radioactive waste categories are operational worldwide.

8. Advanced nuclear reactors and their applications — seen as capable of contributing to the global transition towards more sustainable, affordable and reliable energy systems — are gaining momentum in every region of the world. Such technology, which is suitable for integration into future carbon-free power systems with large shares of variable renewable sources, includes small and medium sized or modular reactors (SMRs).

9. There is growing interest in using nuclear energy for non-electric applications in desalination, hydrogen production, and district heating and cooling, as well as in several energy-intensive industrial applications. SMRs are particularly suitable for such applications, also known as cogeneration, which can offset a significant part of nuclear power generation costs.

10. Substantial progress is visible at the ITER construction site, with more than 73% of the civil work complete. ITER is expected to start operation at full fusion power around 2035. Wide-ranging fusion research and development programmes are also under way in several Member States. One important milestone is the construction of the JT-60SA machine, a superconducting tokamak being built in Naka, Japan, as an international collaboration between Europe and Japan.

11. The 250 research reactors in operation in 54 countries continue to play a strategic role in supporting the medical, industrial, educational and nuclear power sectors. In total, 9 research reactors are under construction in 6 countries, and 14 research reactors are planned in 11 countries. Research reactors are key national facilities for the development of nuclear science and technology infrastructure and programmes. In 2019, one research organization, the Korea Atomic Energy Research Institute, became an IAEA-designated International Centre based on Research Reactor.

12. To date, 99 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 2019, preparations began for the return of HEU fuel from the IVG.1M research reactor in Kazakhstan to the Russian Federation following the conversion of IVG.1M to LEU fuel. Preparations also began for the down-blending of HEU fuel of the IGR research reactor in Kazakhstan to the enrichment level below 20%. By the end of 2019, the programme for the return of US-origin HEU fuel had completed the removal of approximately 1600 kg of fresh and spent HEU research reactor fuel, the Gap Remove Program completed the removal or confirmed disposition of approximately 2875 kg of HEU fuel, and the Russian-origin HEU fuel return programme had completed the removal of approximately 2300 kg.

13. Radiation technologies fulfil the key principles of ‘green’ chemistry and provide manifold possibilities in the processing of materials such as polymers, also known as plastics, via the controlled formation or cleavage of chemical bonds. The performance of radiation technologies has been comprehensively proven in polymer chemistry, including the innovative modification of the properties of polymers and the creation of unique polymeric materials and composites, as well as in the recycling of polymer wastes. Interest in the technology is growing, and Member States are increasingly requesting the adaptation of radiation technologies to the global challenge of plastic waste recycling.

14. Boron neutron capture therapy (BNCT) is a neutron-based technique that allows selective irradiation at the tumour cellular level. BNCT is especially suitable for the treatment of brain, head, neck and skin cancers. Using the reaction between a neutron and boron to selectively destroy only cancer cells, BNCT could become a treatment that differs radically from conventional radiotherapy and promises to be a viable option for cancer treatment. Many advances have been made in BNCT at participating centres worldwide. Significant progress has been made in optimizing boron compounds and in the control of their accumulation in tumour cells, and 3D dose calculation systems have been developed. There is renewed interest in the subject due to a technological breakthrough made in the compact accelerator-based production of neutrons, which allows installation of these facilities in hospitals and cancer research centres.

15. Protein quality is highly important in meeting the nutritional needs of populations across the developing world, in particular during pregnancy and early childhood. Amino acids play a key role in achieving healthy growth in early life. The new minimally invasive isotope method based on the use of deuterium and carbon-13 measures the true ileal digestibility of indispensable amino acids and allows for the assessment of the protein quality of food in humans. This new method will help in identifying good-quality plant protein sources, specifically legume proteins, for human consumption and will serve as a basis for formulating protein quality recommendations for humans by the Food and Agriculture Organization of the United Nations.

16. Biodosimetry methods help to identify radiation exposure in humans and quantify it. Retrospective biodosimetry may even help reveal radiation exposure received years before. Biodosimetry methods have recently been introduced to radiation oncology and nuclear medicine, as well as diagnostic and interventional radiology.

17. A new web-based tool, the Medical Isotope Browser, has been developed, making it possible to directly predict the production yield of a medical isotope on the basis of user input. The Medical Isotope Browser can be used by medical scientists and the radiopharmaceutical industry to discover radioisotope production routes not yet explored. This will contribute significantly to the fight against cancer and other diseases. The production of medical isotopes for therapy or diagnosis depends on very complex nuclear reaction processes, which are only available to nuclear physicists via measurements and nuclear reaction theories. The Medical Isotope Browser makes this fundamental information accessible to many non-specialist users through a graphical user interface for isotope production.

18. Invasive species are increasing in prevalence and they are contributing to global biodiversity loss. The sterile insect technique (SIT), deployed as an important component of an area-wide integrated pest management approach, can prevent the establishment of, contain or eradicate, an invasive population without leaving an ecological footprint. Improved technologies and protocols for mass-production, sterilization and the release of sterile insects have greatly enhanced the cost-effectiveness of area-wide integrated pest management with an SIT component. This has opened the door to expanding the use of this technology to other key insect pests, including high-profile invasive pests that affect plants, animals and human health. Analyses indicate that preparations to enable a rapid response before a pest is established are much cheaper than later eradication campaigns.

19. Numerous foods are sold at premium prices because of ‘added-value’ labelling claims related to specific geographical origins, production methods and unique characteristics. Origin-linked products can be part of a virtuous circle of sustainable quality based on the preservation of local resources, including agricultural, artisanal, ethical and nutraceutical labelling — specifications that add value to food products. In order to protect consumers from food fraud and potential unintended food safety issues, analytical methods are required to verify such added-value claims in support of traceability systems. Several nuclear, isotopic and related techniques have proven suitable for verifying a wide range of added-value labelling claims. Such techniques have great potential to support traceability systems that protect and promote food products with added-value labelling claims. Wider use of this technology by Member States will ultimately safeguard consumers and reputable producers, ensure regulatory and ethical compliance, stimulate domestic markets, and reduce barriers to international trade.

Nuclear Technology Review 2020
Main Report

A. Power Applications

A.1. Nuclear Power Today

20. As of 31 December 2019, there were 443 operational nuclear power reactors worldwide, with a total capacity of 392.1 GW(e)[1] (Table A-1). Of these, 83 were light water moderated and cooled, 11% heavy water moderated and cooled, 3% light water cooled and graphite moderated, and 3% gas cooled (Figure A-2). Three were liquid metal cooled fast reactors. Nearly 89% of nuclear generated electricity was produced by 376 light water reactors.

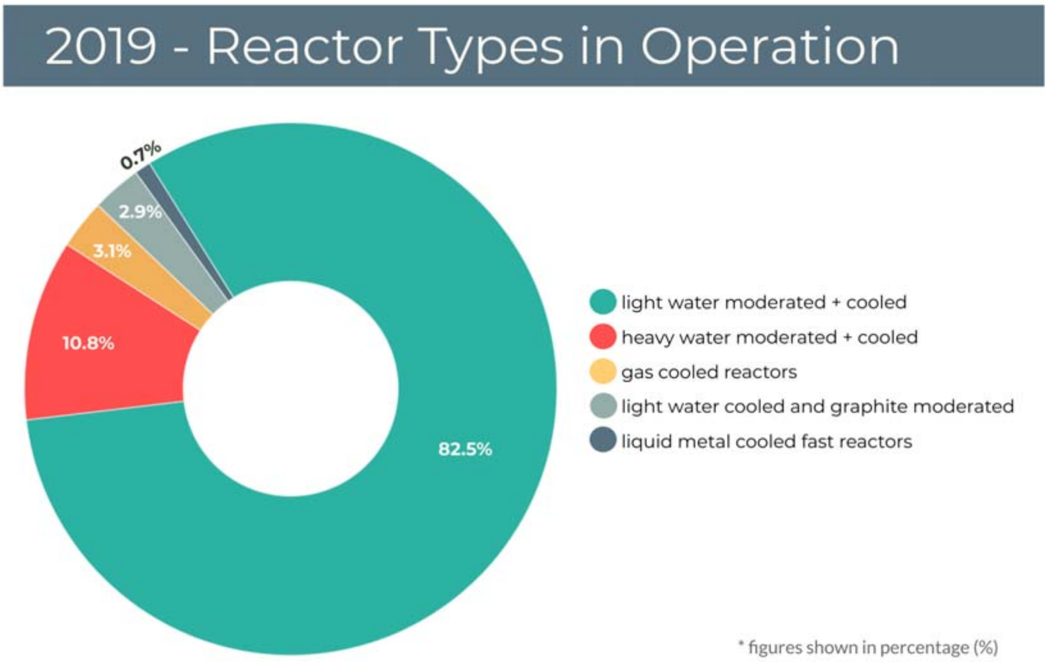


FIG. A-2. Nuclear power reactors by type. (Source: IAEA Power Reactor Information System www.iaea.org/pris)

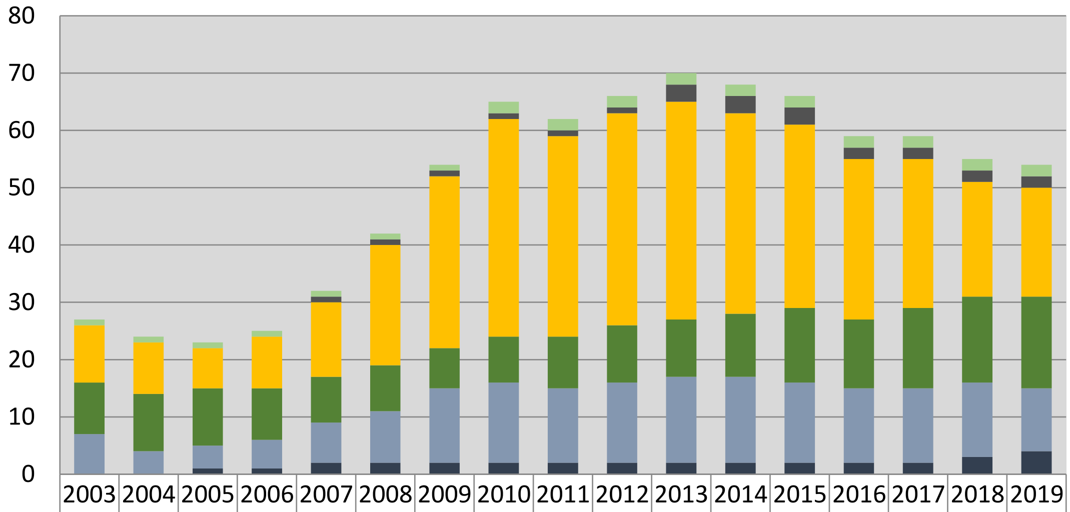
21. In 2019, six new pressurized water reactors (PWRs) were connected to the grid: two in China (Taishan-2, 1660 MW(e) and Yangjiang-6, 1000 MW(e)), one in Republic of Korea (Shin-Kori-4, 1340 MW(e)) and three in the Russian Federation (Novovoronezh 2-2, 1114 MW(e), Akademik Lomonosov-1, 30 MW(e) and Akademik Lomonosov-2, 30 MW(e)), bringing the total added capacity worldwide during the year to 5174 MW(e). A total of 13 reactors were permanently shut down: Chinshan-2 in Taiwan, China; Philippsburg-2 in Germany; Genkai-2 and Fukushima Daini 1–4 in Japan;

[1] 1 GW(e), or gigawatt (electrical), equals one thousand million watts of electrical power.

Wolsong-1 in the Republic of Korea; Bilibino-1 in the Russian Federation; Ringhals-2 in Sweden; Muehleberg in Switzerland; and Pilgrim-1 and Three Mile Island-1 in the United States of America.

22. As of 31 December 2019, 54 reactors were under construction. Construction started on Zhangzhou-1 and Taipingling-1 in China, Bushehr-2 in the Islamic Republic of Iran, Kursk 2-2 in the Russian Federation and Hinkley Point C-2 in the United Kingdom. Expansion, as well as near and long term growth prospects, remains centred in Asia (Figure A-3), where 35 reactors are under construction. Asia is also home to 61 of the 74 new reactors that have been connected to the grid since 2005.

Number of reactors under construction by region



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
America - Latin	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
America - Northern	0	0	0	0	1	1	1	1	1	1	3	3	3	2	2	2	2
Asia - Far East	10	9	7	9	13	21	30	38	35	37	38	35	32	28	26	20	19
Asia - Middle East and South	9	10	10	9	8	8	7	8	9	10	10	11	13	12	14	15	16
Europe - Central and Eastern	7	4	4	5	7	9	13	14	13	14	15	15	14	13	13	13	11
Europe - Western	0	0	1	1	2	2	2	2	2	2	2	2	2	2	2	3	4

FIG. A-3. Number of reactors under construction by region.
(Source: IAEA Power Reactor Information System www.iaea.org/pris)

Table A-1. Nuclear power reactors in operation and under construction in the world (as of 31 December 2019)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2019		Total Operating Experience through 2019	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	3	1641	1	25	7.9	5.9	88	2
ARMENIA	1	375			2.0	27.8	45	8
BANGLADESH			2	2160				
BELARUS			2	2220				
BELGIUM	7	5930			41.4	47.6	303	7
BRAZIL	2	1884	1	1340	15.2	2.7	57	3
BULGARIA	2	2006			15.9	37.5	167	3
CANADA	19	13554			94.9	14.9	769	6
CHINA	48	45518	11	10564	330.1	4.9	370	1
CZECH REPUBLIC	6	3932			28.6	35.2	170	10
FINLAND	4	2794	1	1600	22.9	34.7	163	4
FRANCE	58	63130	1	1630	382.4	70.6	2280	4
GERMANY	6	8113					846	7
HUNGARY	4	1902			15.4	49.2	138	2
INDIA	22	6255	7	4824	40.7	3.2	526	11
IRAN, ISLAMIC REPUBLIC OF	1	915	1	974	5.9	1.8	8	4
JAPAN	33	31679	2	2653	65.7	7.5	1899	6
KAZAHSTAN							25	10
KOREA, REPUBLIC OF	24	23172	4	5360	138.8	26.2	572	2
MEXICO	2	1552			10.9	4.5	55	11
NETHERLANDS	1	482			3.7	3.1	75	0
PAKISTAN	5	1318	2	2028	9	6.6	82	5
ROMANIA	2	1300			10.4	18.5	35	11
RUSSIAN FEDERATION	38	28437	4	4525	195.5	19.7	1334	5
SLOVAKIA	4	1814	2	880	14.3	53.9	172	7
SLOVENIA	1	688			5.5	37.0	38	3
SOUTH AFRICA	2	1860			13.6	6.7	70	3
SPAIN	7	7121			55.9	21.4	343	1
SWEDEN	7	7740			64.4	34.0	467	0
SWITZERLAND	4	2960			25.4	23.9	224	11
TURKEY			1	1114	NA	NA		
UKRAINE	15	13107	2	2070	78.1	53.9	518	6
UNITED ARAB EMIRATES			4	5380				
UNITED KINGDOM	15	8923	2	3260	51.0	15.6	1619	7
UNITED STATES OF AMERICA	96	98152	2	2234	809.4	19.7	4505	8
Total [b,c,d]:	443	392098	54	57441	2586.2		18329	10

a. Source: Agency's Power Reactor Information System (PRIS) (www.iaea.org/pris).
b. Total nuclear electricity supplied in 2019 does not include data from seven German reactor units, as information for these units was not submitted by the time of publication.
c. The total figures include the following data from Taiwan, China: 4 units, 3844 MW(e) in operation; 2 units, 2600 MW(e) under construction.
d. 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 (224 years, 1 month).

A.1.1. Operating Countries

23. At the end of 2019, more than 66% of the 443 operating nuclear power reactors, constituting 256.3 GW(e) of net capacity, had been in operation for over 30 years. Nuclear power reactors in service for over 40 years accounted for 17% of global capacity. Long term operation and ageing management programmes are being implemented for an increasing number of NPPs.

In 2019, a total of 71 nuclear power reactors (14 in Asia and 57 in Europe) were used worldwide to generate 2146.72 gigawatt-hours (GW·h) of electrical equivalent heat to support non-electrical applications of nuclear energy. Of these reactors, 10 supported desalination (producing 48.01 GW·h), 56 district heating (1870.6 GW·h) and 32 industrial process heat applications (1248.01 GW·h).

24. Two fast reactors are in operation in the Russian Federation. Beloyarsk 3, with a net capacity of 560 MW(e), has supplied 140 777 GW·h of electricity since being connected to the grid in 1980. Beloyarsk 4, with a net capacity of 820 MW(e), has supplied 13 066 GW·h electricity since entering commercial operation in 2016.

25. In Africa, Eskom began overhauling its Koeberg reactors in South Africa, with an aim to extend their operational lifetimes by at least 20 years.

26. In Asia, China began using two recently commissioned AP1000 type reactors for cogeneration. In Taiwan, China, an amendment was passed eliminating a requirement that all NPPs cease operations in 2025, fulfilling the results of a referendum held in November 2018. In India, Kakrapar Atomic Power Station was restarted after the coolant channel and feeder tubes were replaced.

27. Japan’s focus remains on remediation at the Fukushima Daiichi NPP site, as well as on restarting idle NPPs. Since their shutdown following the Fukushima Daiichi accident, nine reactors (all PWRs) have been restarted. With safety being the priority, the Strategic Energy Plan (2018) foresees nuclear as an important baseload power source for achieving an ‘optimal energy mix’ by 2030 and as an option for decarbonization by 2050.

28. In Europe, France postponed for 10 years a planned reduction of its nuclear power fleet and started upgrade and maintenance work at its 900 MW(e) Tricastin-1 reactor, which could enable operation of the unit for another decade. However, the multiyear energy plan published at the beginning of 2019 sets 2035 as the deadline for decreasing the nuclear share in the country’s electricity mix to 50%. To reach this target, 14 reactors will be shut down for a total capacity decrease of 12 600 MW(e). In Belgium, concrete repair work at Doel-3 was completed, while a modernization programme at Romania’s Cernavodă NPP was under way. In Sweden, lifetime extensions of Forsmark NPP units 1 and 2 were approved, while in Ukraine a project was under way to extend by 10 years the operational lifetime of the Ukraine-3 reactor.

29. In Latin America, the capacity of the Embalse NPP in Argentina was increased by 1.33%, and its operational lifetime was extended by 30 years.

30. In North America, Canada made significant investments in lifetime extension projects, with Darlington-2 set to be restarted in 2020. In the United States of America, most existing reactors have had their operational lifetimes extended to 60 years. The Nuclear Regulatory Commission (NRC) has approved Florida Power & Light’s application for an additional 20 years of operation for Turkey Point

Nuclear Generating Units 3 and 4. This is the first time the NRC has issued renewed licenses authorizing reactor operation from 60 to 80 years.

31. The reliability of NPPs has continued to improve over time. Figure A-4 shows the number of unplanned manual and automatic scrams or shutdowns per 7000 hours (approximately one year) of operation per unit.

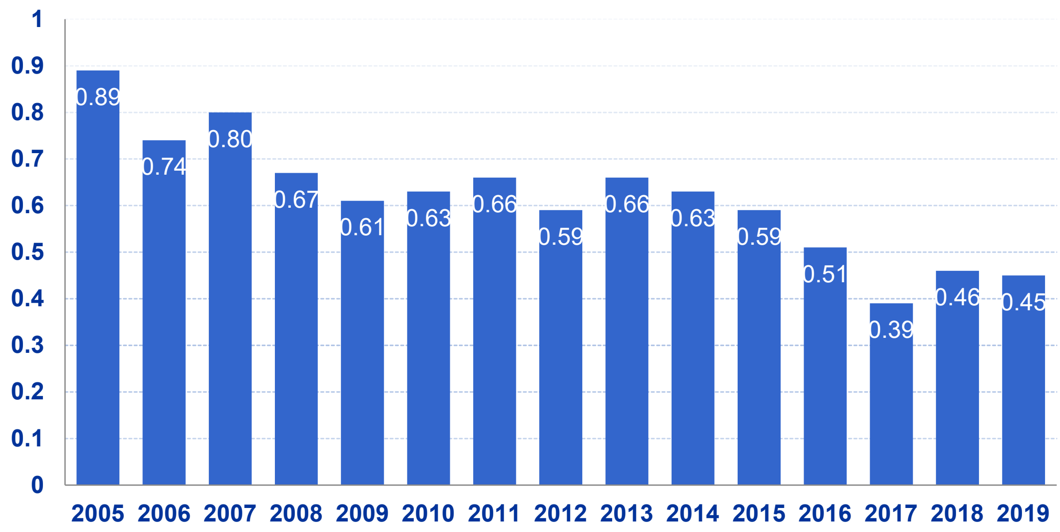


FIG. A-4. Mean rate of scrams: the number of automatic and manual unplanned scrams per 7000 hours of operation of a unit. (Source: IAEA Power Reactor Information System www.iaea.org/pris)

A.1.2. New Projects Within Existing Nuclear Power Programmes

32. Of the 30 operating Member States, 15 are actively constructing additional nuclear power units. This represents 45 reactor projects with a total net capacity of 46 567 MW(e). Figure A-5 lists these countries according to the number of units each is constructing and their total net capacity.

FIG. A-5. Fifteen Member States with existing nuclear power programmes are constructing additional nuclear power units

33. In 2019, China connected a second EPR reactor (Taishan-2) to the grid as well as an APCR-1000 (Yangjiang-6), increasing the total number of operating nuclear power units to 48. Together with four operating reactors in Taiwan, China's total nuclear power capacity reached 49362 MW(e). Meanwhile, Finland and France announced plans to connect their EPR reactors to grid in July 2020 and at the end of 2022, respectively. In the United Kingdom, the first concrete was laid for the foundations of Hinkley Point C.

34. In June 2019, Rosenergoatom in the Russian Federation received a licence to operate the Akademik Lomonosov floating nuclear power station until 2029, and in December the reactors were connected to the grid. (See paragraph 152 for more information).

35. India, with 22 reactors in operation and seven under construction, is expected to bring 21 new nuclear power reactors, with a combined generating capacity of 15 700 MW(e), into operation by 2031.

A.1.3. Newcomers

36. Among the 28 Member States that have expressed interest in nuclear power, 18 have initiated studies on nuclear power infrastructure, four have already taken a decision and are building institutional capacity and developing the necessary infrastructure in preparation for contracting and financing of an NPP, one (Egypt) has signed a contract and is preparing for construction, two (Bangladesh and Turkey) have commenced construction and another two (Belarus and UAE) are nearing completion of the construction of their first NPP.

37. In the United Arab Emirates (UAE), construction of the four reactors of Barakah NPP is almost complete, and the issuance of the operating licence for the first two units is imminent. Fuel loading of Unit 1 is scheduled for the first quarter of 2020 and of Unit 2 a year later. An Emergency Preparedness Review (EPREV) follow-up mission was conducted in September 2019.

38. In Belarus, construction of the first NPP at Ostrovets is ongoing. Fuel loading of the first unit is scheduled for the first quarter of 2020, subject to regulatory approval, with commissioning of the second unit scheduled for 2021. Belarus hosted an IAEA State Systems of Accounting for Control of Nuclear Material Advisory Service (ISSAS) mission and a Pre-Operational Safety Review Team (pre-OSART) mission in August 2019, and requested an Integrated Nuclear Infrastructure Review (INIR) Phase 3 mission to be conducted in February 2020.

39. In Bangladesh, construction of Rooppur NPP is under way, with commissioning of Units 1 and 2 expected in 2023 and 2024, respectively. The site survey for a second NPP project is in progress. An Integrated Regulatory Review Service (IRRS) mission is foreseen in 2020. International Physical Protection Advisory Service (IPPAS) and ISSAS missions are foreseen in 2021.

40. In Turkey, construction of the first unit of Akkuyu NPP continued, with anticipated commissioning in 2023, while a construction licence was issued for the second unit. An IPPAS mission is planned for 2020 and an IRRS mission is foreseen in 2021.

41. In Egypt, following the site licence approval for a four-unit NPP at El Dabaa in March 2019, construction is planned to begin in mid-2020, subject to regulatory approval. Commissioning of the first unit is foreseen to be complete in 2026 and of the other units by 2028. Egypt hosted a Site and External Events Design (SEED) mission in January 2019 and an INIR Phase 2 mission in October–November 2019.

42. Saudi Arabia continued preparatory work for the parallel construction of a small modular reactor (SMR) and two large NPPs. Site characterization for the large NPPs is ongoing. Construction of the system-integrated modular advanced reactor (SMART) is expected to begin in 2023, with commissioning foreseen in 2028.

43. Jordan continued to perform technology assessments for selecting appropriate SMRs. A 200–400 MW(e) power plant based on the selected SMR technology is to be commissioned by 2030. A large NPP is foreseen in the longer term (post 2030).

44. Nigeria plans to construct four reactor units, with the first unit officially expected to be in operation in 2027. A decision to resume the pre-feasibility study before completing the feasibility study may result in an additional delay of the target date.

45. In Poland, following public consultations, a decision to proceed with the nuclear power programme and construction of an NPP is anticipated in 2020. Commissioning of the first unit is foreseen in 2033.

46. Member States continue to benefit from Agency assistance in understanding the commitments and obligations associated with developing the necessary infrastructure for a nuclear power programme, based on the Milestones Approach, which supports the establishment of safe, secure and sustainable nuclear power programmes.

In 2019, the Integrated Work Plans and Country Nuclear Infrastructure Profiles of eight Member States were updated through national Technical Cooperation projects in: Saudi Arabia (January), Turkey (January), Jordan (February), Belarus (March), Poland (March), Philippines (November), Kenya (December) and Bangladesh (December). With an INIR Phase 2 mission to Egypt and an INIR Phase 1 follow-up mission to Ghana conducted in 2019, the number of INIR missions deployed since 2009 reached 29 in 21 Member States. Moreover, around 490 participants from 52 embarking and expanding countries benefitted from participation in 31 interregional training activities within the framework of Technical Cooperation project INT2018, "Supporting Knowledgeable Decision-making and Building Capacities to Start and Implement Nuclear Power Programmes" (Figure A-6).

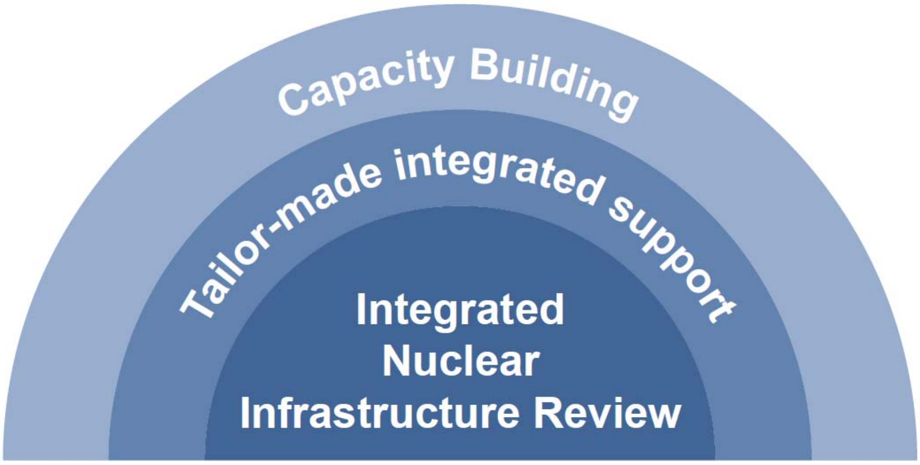


FIG. A-6. IAEA's integrated support to countries embarking on new nuclear power programmes helps lay the foundations for a first nuclear power plant through expert peer review missions, tailor-made activities to address identified gaps, and capacity building.

A.2. The Projected Growth of Nuclear Power

47. The Agency's 2019 projections (Figure A-7), prepared in consultation with regional experts and reflecting the latest information on policy and market conditions, offer a mixed estimate of nuclear power's future contribution to global electricity generation, depending in part on whether significant new capacity can be added to offset potential reactor retirements. In the low projection to 2030, net installed nuclear electricity generation capacity gradually declines and then rebounds to 371 GW(e) by 2050. In the high case, capacity increases to 496 GW(e) by 2030 and to 715 GW(e) by 2050. This represents a 25% increase in capacity over current levels by 2030 and an 80% increase by 2050. Nuclear power's share of total world electrical capacity will be about 6% in the low case and 12% in the high case by the middle of the century, compared with about 10% today.

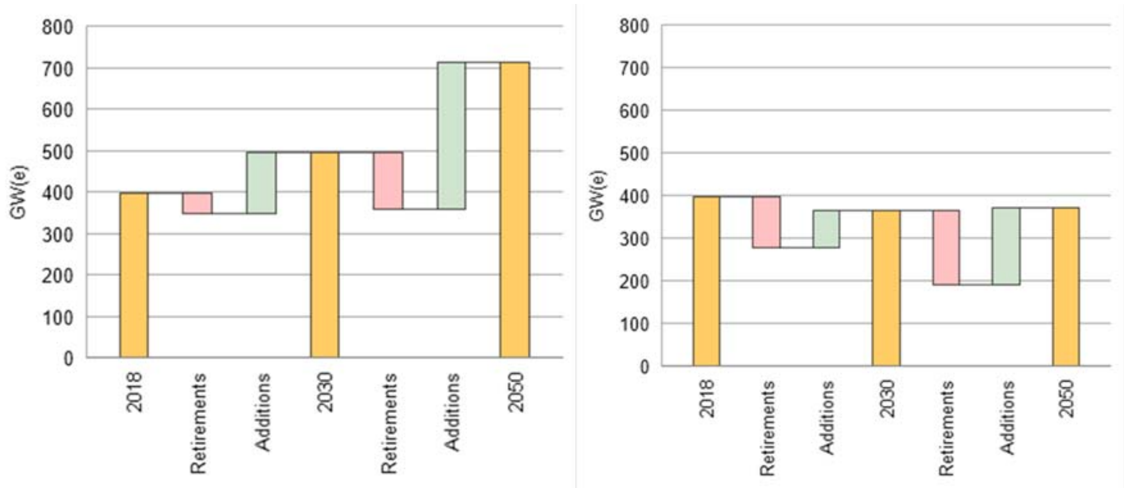


FIG. A-7. High (left) and low (right) projections for world nuclear capacity.
(Source: Energy, Electricity and Nuclear Power Estimates for the Period up to 2050,
IAEA Reference Data Series No. 1,2018)

48. The wide range in the projections is due to uncertainty regarding the replacement of the large number of reactors scheduled to be retired around 2030 and beyond, particularly in North America and Europe. However, the 2019 projections contain fewer uncertainties compared with previous years owing to recent announcements on the future of the existing fleet in some regions and long-term plans for expansion. Significant new capacity may be needed to offset possible reactor retirements resulting from age, competitiveness or other factors.

49. Together with other low carbon technologies, nuclear energy can meet increasing demands for electricity and non-electric energy up to 2050 as part of a sustainable energy transition. A total of 90% of stringent climate change mitigation scenarios report nuclear generation in 2050 above the Agency's latest low projection, while 60% exceed the Agency's high projection.

> Global energy scenarios from the Intergovernmental Panel on Climate Change and the International Energy Agency, as well as from governments, industry and non-governmental organizations, envision an increasing role for nuclear power in climate change mitigation in order to achieve the goals of the Paris Agreement. This fact was also reflected in the conclusions of the International Conference on Climate Change and the Role of Nuclear Power organized by the Agency in October 2019, in cooperation with OECD/NEA.

50. Compared to current policy and market trends reflected in the Agency's projections, and the modest mitigation targets in nationally determined contributions submitted by countries under the Paris Agreement, the scenarios illustrate the need for additional efforts to unlock the substantial mitigation potential of nuclear power to achieve ambitious global climate goals.

A.3. Fuel Cycle

A.3.1. Front End

Uranium resources and production

Uranium spot prices continued to remain depressed in 2019 and were generally in the range of $52/kgU to $57/kgU. The spot price for uranium has remained relatively unchanged since 2018 (ranging from $47/kgU to $59/kgU) and depressed since 2013, resulting in a significant reduction in uranium exploration programmes.

51. New uranium projects in either the planning or development stage remained on hold, and a number of previously active uranium mines and processing facilities remained in a state of care and maintenance in response to the low uranium spot prices. The global production of uranium from active uranium mines in 2019 is forecast to be similar to that of 2018, which was 53 498 tonnes of uranium (tU). This represents about a 15% reduction in global uranium production since 2016.

52. Kazakhstan continued to be the world's leading uranium producer. In 2019, there were eight uranium mines in operation, all of them utilizing in-situ recovery, and total combined production is forecast to be between 22 000 and 23 000 tU (slightly higher than the 2018 production levels of 21 705 tU). In Canada, the second largest producer, the Cigar Lake mine and the associated McClean Lake mill were the only active uranium producers in 2019, with forecasts of about 7000 tU produced, while two mines and two mills were in a state of indefinite care and maintenance owing to low uranium prices. In Australia, the Ranger uranium operation winded down its production in 2019 (with forecasts of between 1400 and 1800 tU processed from stockpiles), as it advanced into decommissioning and remediation. The Olympic Dam copper mine produced uranium (about 3000 tU in 2019) as a co-product. The Four Mile in-situ recovery operation is forecast to have produced about 1200 tU in 2019. Total forecast uranium production in Australia for 2019 ranges between 5600 tU and 5800 tU (slightly lower than 2018, when it produced 6517 tU, owing to the reduced production at the Ranger mine).

53. In Africa, there are active uranium mines in Namibia and Niger. Namibia has four developed uranium mines, two in operation (Rössing and Husab, with forecast production amounts of 2200 tU and 3028 tU for 2019, respectively) and two in care and maintenance owing to low uranium prices (Langer Heinrich and Trekkopje). However, a pre-feasibility study was released in late 2019 to restart the Langer Heinrich uranium mine within 12 months. Niger has two operating uranium mines: Somair and Cominak. Production rates for these two mines are expected to be the same in 2019 as in 2018 (1769 tU for the Somair mine and 1115 tU for the Cominak mine). Overall, uranium production in Africa is forecast to be 8100 tU in 2019.

54. China's national policy is to ensure an abundant supply of uranium resources for the sustainable development of nuclear power over the medium- and long-term. . China currently has in operation seven domestic uranium mines with a combined annual output of 1650 tU. In addition, China is engaged in several foreign mineral development projects, mainly in Kazakhstan, Namibia and the Niger.

55. Feasibility studies continued for the recovery of uranium in central Jordan, and a pilot plant at the central Jordan site (based on heap leaching technology) will be commissioned in 2020. A project for a uranium concentrate manufacturing plant in Salamanca, Spain, was also under evaluation.

Conversion and enrichment

56. Current conversion and enrichment capacity is more than sufficient to meet the global demand, albeit with a segmented market and production centred on a few suppliers. At present, five producers meet the majority of global demand for uranium hexafluoride (UF_6), with a nameplate capacity of 62 000 tU per year, but a capacity utilization of only 56% (about 34 500 tonnes produced) in 2019 (Figure A-8). The global supply of enriched uranium primarily originates from commercial enrichment plants as well as secondary supplies, such as previously produced enriched uranium or tails re-enrichment. Most enrichment capacity is focused in Europe and the Russian Federation (Orano, URENCO and the State Atomic Energy Corporation "Rosatom"), although the China National Nuclear Corporation (CNNC) is developing as a domestic provider of enrichment services in China and plans to offer these services internationally in the future.

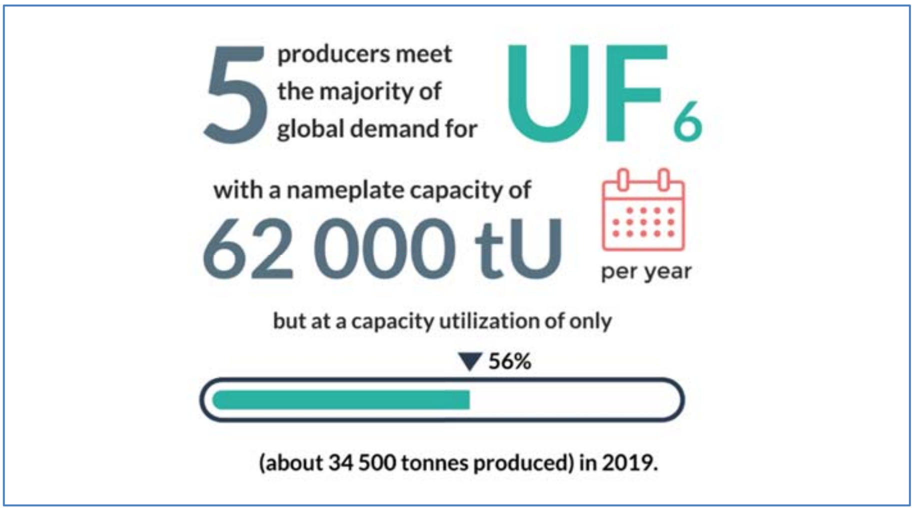


FIG. A-8. Global conversion and enrichment capacity in 2019.

Fuel fabrication

57. To comply with the Euratom Supply Agency's strategy for diversification of nuclear fuel supplies, Bulgaria's Kozloduy NPP announced in February 2019 that it had hired the Swedish branch of Westinghouse Electric Company to study options for licensing and integration of improved fuel for its plant's two units (5 and 6) under a BGN 3.1 million ($1.8 million) contract. The Czech power company ČEZ announced in April 2019 that it would load an experimental batch of six fuel assemblies (FAs) made by the Swedish branch of Westinghouse into Unit 1 of its Temelín NPP. The Russian fuel company TVEL (part of Rosatom) is the main supplier of nuclear fuel for Kozloduy NPP and Temelin NPP and delivers advanced fuel with increased resource (TVSA-12 and TVSA-T.mod.2) to these NPPs on a regular basis.

58. In February 2019, Westinghouse Electric Company announced the launch of its new generation of FAs designed for boiling water reactors (BWRs) (commercial name: Triton11, technical name: 11x11 BWR) to significantly reduce the cost of the fuel cycle and to increase the reliability and safety of operation. The new assemblies will first be tested in units 1 and 2 of Olkiluoto NPP, which have 900 MW(e) ABB-III BWRs, in Finland.

59. In March 2019, the CNNC completed the long-term irradiation test of a domestic nuclear FA for PWRs and started mass production of China Fuel 3 FAs (manufactured at the CNNC's main PWR fuel fabrication plant in Yibin, Sichuan province, China, using fuel pellets from Kazakhstan's Ulba Metallurgical Plant) for the domestically-designed Hualong One (HPR1000) PWR.

60. Two experimental FAs with four different combinations of advanced fuel pellets (made of uranium dioxide and uranium–molybdenum alloy with increased density and thermal conductivity) and cladding materials (made of chromium-coated zirconium or chromium–nickel alloys) manufactured by TVEL were loaded into the MIR research reactor at the Research Institute of Atomic Reactors in Dimitrovgrad, Russian Federation, in January 2019 and tested during 2019.

61. Southern Nuclear and Framatome announced in April 2019 that the first accident tolerant FAs containing chromia-enhanced fuel pellets and chromium-coated zirconium alloy cladding had been loaded into unit 2 of Plant Vogtle in the state of Georgia, United States of America, during the spring refuelling outage. BWX Technologies announced in October 2019 that it was in the process of restarting its existing uranium oxycarbide tristructural isotropic fuel production line at its Lynchburg facility in the state of Virginia, United States of America.

62. In January 2019, TVEL signed a contract with India’s Department of Atomic Energy to supply uranium fuel pellets for the Tarapur Atomic Power Station’s BWR reactors (50 tonnes of fuel pellets had been delivered by November 2019). In July 2019, TVEL signed a contract with Suneng Nuclear Power Corporation and China Nuclear Energy Industry Corporation, both subsidiaries of the CNNC, to supply nuclear fuel for Units 7 and 8 of China’s Tianwan NPP in Jiangsu province. Also in July 2019, TVEL delivered a batch of nuclear fuel to the Chinese Experimental Fast Reactor. In August 2019, TVEL was designated as the single-source supplier of nuclear fuel for both units of Rooppur NPP in Bangladesh for their entire lifecycle.

63. The first industrial batch of mixed oxide fuel consisting of 18 FAs manufactured at the Mining and Chemical Complex in Zheleznogorsk, Russian Federation, was received and loaded into the BN-800 fast reactor at the Beloyarsk NPP in August 2019. Reactor testing of regenerated mixture fuel (a reprocessed mixture of uranium and plutonium) for water cooled, water moderated power reactors (VVERs) and of nitride mixed uranium–plutonium fuel for fast reactors was also under way in the Russian Federation.

64. In September 2019, Ukraine’s National Nuclear Energy Generating Company “Energoatom” and Westinghouse signed a preliminary agreement for Westinghouse to manufacture fuel for Ukraine’s VVER-440 reactors. In September 2019, lead test assemblies of Westinghouse EnCore fuel rods, manufactured at the Idaho National Laboratory in the United States of America and consisting of high-density ADOPT pellets (Westinghouse’s chromia- and alumina-doped uranium dioxide pellets for improved fuel economics) and uranium silicide pellets (providing benefits in improved safety and better plant economics) enclosed in a chromium-coated zirconium cladding (for enhanced oxidation and corrosion resistance), were loaded into unit 2 of Exelon’s Byron NPP during a scheduled refuelling outage.

A.3.2. Assurance of Supply

65. In December 2010, the Agency’s Board of Governors approved the establishment of the IAEA Low Enriched Uranium (LEU) Bank. The Agency and Kazakhstan completed the basic legal framework in 2015 to establish the IAEA LEU Bank at the Ulba Metallurgical Plant site in Ust-Kamenogorsk, Kazakhstan.

66. The IAEA LEU Bank in Kazakhstan (Figure A-9) was established and became operational upon the receipt in the IAEA LEU Storage Facility of the 32 full 30B cylinders from the Supply Contract with Orano Cycle on 17 October 2019. Additionally, 28 full 30B cylinders from the Supply Contract with Kazatomprom were received on 10 December 2019.

FIG. A-9. IAEA LEU Storage Facility in Kazakhstan with canisters of LEU.
(Photo: Kazakhstan Ministry for Foreign Affairs)

67. Other assurance of supply mechanisms in place are described in the Nuclear Technology Review 2012 (document GC(56)/INF/3).

A.3.3. Back End

Spent fuel transport

68. In the United States of America, the Nuclear Regulatory Commission (NRC) certified Holtec International's HI-STAR 100MB transport package in August 2019. The design is an enhancement of an earlier model to enable the transport fuel with higher burnups and shorter cooling times in comparison to its predecessor. Transfers of spent fuel at the San Onofre NPP resumed in May 2019, following a suspension in August 2018. The NRC approved the restarting of operations after concluding an investigation into an incident during the emplacement of a spent fuel canister into the storage vault.

69. In August, the Government of Belarus formally approved a spent fuel management strategy for the country's new NPP. The strategy involves sending the spent fuel from the NPP to the Russian Federation for reprocessing and the return of the radioactive waste for disposal in Belarus.

70. In the Russian Federation, the first transfers of damaged spent nuclear FAs from the Lepse floating technical base at the Nerpa shipyard to Murmansk were undertaken. The fuel will eventually be sent to Mayak plant for reprocessing as part of a programme managed by the European Bank for Reconstruction and Development (EBRD).

Spent fuel storage

71. To date, around 400 000 tonnes of heavy metal have been discharged from NPPs as spent nuclear fuel, of which about 30% has been reprocessed. The rest is stored either in reactor pools or in the 151 away-from-reactor spent fuel storage facilities in 27 countries. In 2019, more than 6630 RBMK-1000 spent FAs from the Leningrad and Kursk NPPs were transferred and placed in dry storage at the Mining and Chemical Complex.

72. In Japan, photographs of fuel debris within the primary containment vessel of Fukushima Daiichi NPP Unit 2 were released in February. The photographic survey was followed by a further survey utilizing a remote probe with manipulation capabilities; it was able to pick up debris samples from five locations for further characterization and analysis. The removal of 566 spent FAs from the Fukushima Daiichi NPP Unit 3 pool began in April 2019 following work to clear the reactor service floor of rubble from the accident. The FAs will be taken to the centralized on-site pool.

73. In the United Kingdom, a five-year programme to repackage historical plutonium canisters at Sellafield commenced in August 2019, with the opening and repackaging of the first canister into a modern and more robust outer can. Defueling of the Magnox fleet of reactors was completed, with the

final spent fuel transfers from the Wylfa and Calder Hall sites completed in September. The spent fuel was transported to Sellafield for storage prior to reprocessing. Ongoing work to remove the remaining breeder elements from the Dounreay fast reactor has reached the halfway point. Specialized remote tools were required to remove the jammed elements that were left in place when the reactor was shut down in 1977.

74. In Ukraine, the Chornobyl Interim Spent Nuclear Fuel Storage Facility (for processing and storage facilities for spent fuel arisings from Chornobyl NPP Units 1, 2 and 3) completed the pre-commissioning stage in September 2019 and will formally enter full commissioning once the operator (Chornobyl NPP) obtains an individual operating licence from the regulator.

Spent fuel reprocessing

75. Since the closure of Thermal Oxide Reprocessing Plant in the United Kingdom, the global annual reprocessing capacity for commercial spent fuels is about 4000 tonnes per year (which may increase once the Rokkasho Reprocessing Plant is fully operational again).

A.4. Decommissioning, Environmental Remediation and Radioactive Waste Management

A.4.1. Decommissioning of Nuclear Facilities

76. As of 31 December 2019, 186 power reactors have been shut down or are undergoing decommissioning across the world. Of those, 17 reactors have been fully decommissioned, while more are approaching the final stages of decommissioning. More than 150 fuel cycle facilities have been permanently shut down or are undergoing decommissioning and close to 130 have been decommissioned (Figure A-10).

FIG. A-10. Global status of decommissioning in 2019.

77. As of 31 December 2019, more than 560 research reactors and critical assemblies have been permanently shut down, out of which about 440 have been fully decommissioned; close to 70 research reactors are under active decommissioning and about 60 are under permanent shutdown awaiting decommissioning.

78. In September 2019, the Joint Research Centre of the European Commission signed an agreement with Sogin, Italy's State-owned company responsible for decommissioning and radioactive waste management, concerning the dismantlement of the ISPRA-1 research reactor.

79. Deployment of proven decommissioning technologies and research and development work are delivering continuous improvements, mainly in countries with extensive nuclear power programmes. An example of an effectively used innovative technique is the self-climbing platform designed to assist in the demolition of the ventilation stack of a legacy reprocessing plant at the Sellafield site (Figure A-11).

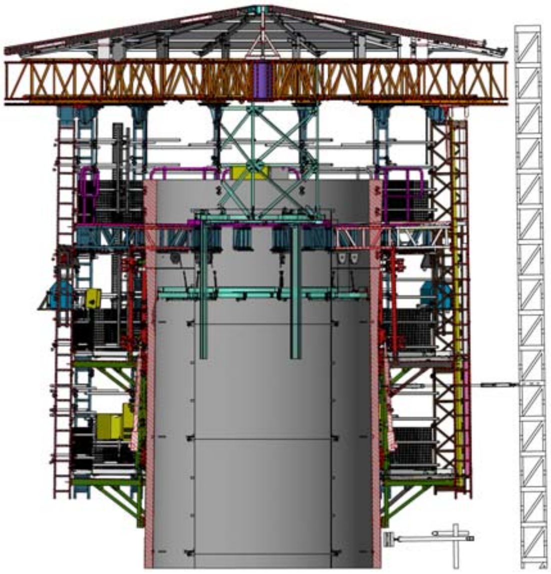


Fig. A-11. Self-climbing platform designed to assist in the demolition of the ventilation stack of a legacy reprocessing plant at the Sellafield site. (Photo: Sellafield Ltd)

80. Progress on NPP decommissioning projects, supported by the European Bank for Reconstruction and Development, continue in Bulgaria, Lithuania, Slovakia and Ukraine. Examples include the removal of steam generators from the Bohunice V-1 NPP reactor hall into the turbine hall for further fragmentation (Figure A-12) and the initiation of Ignalina NPP's project on dismantling its high-power channel-type reactor and on graphite storage.

FIG. A-12. Removal of the last of 12 steam generators weighing 145 tonnes from the decommissioned Bohunice V-1 NPP in Slovakia. (Photo: Nuclear and Decommissioning Company JAVYS)

81. The Stakeholder-based Analysis of Research for Decommissioning or 'SHARE' project proposed by several European Union member countries has been accepted by the European Commission and commenced in mid-June 2019. By the end of 2021, SHARE intends to provide an inclusive road map for research in technical and non-technical fields, enabling stakeholders to jointly improve safety, reduce costs and minimize environmental impact in the decommissioning of nuclear facilities.

82. The Back-end Roadmap was published by the Japan Atomic Energy Agency (JAEA) indicating the long-term policy of JAEA on the decommissioning of its installations as well as the processing and disposal of the associated radioactive waste. It will be subject to an Integrated Peer Review for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (ARTEMIS) review in 2020.

83. In September 2019, Japan's Nuclear Damage Compensation and Decommissioning Facilitation Corporation issued the Technical Strategic Plan 2019 for Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc., including recommendations for determining methods of fuel debris retrieval for Unit 2, the first unit from which debris will be removed. The work on decommissioning of the Fukushima Daiichi NPP site is progressing, including internal investigations of Unit 2 and fuel removal from the spent fuel pool in Unit 3.

A.4.2. Environmental Remediation

84. The site operator Magnox has made good progress with the remediation of the former Liquid Effluent Treatment Plant at the Harwell site in the United Kingdom (Figure A-13). Work on the 4.2-hectare site commenced in February 2018 and, by the end of October 2019, 54 000 tonnes of material had been successfully excavated, assayed and consigned to the appropriate off-site disposal routes. All waste material from the work is packaged in 0.9 cubic metre bulk bags, which are all subject to assay using high resolution gamma spectrometry. Remediation work is forecast to be completed by summer

2020, with work to remove regulatory controls and site reinstatement following in 2021. On completion, the site will be released back to the landowner for reuse as part of the Harwell Campus development.

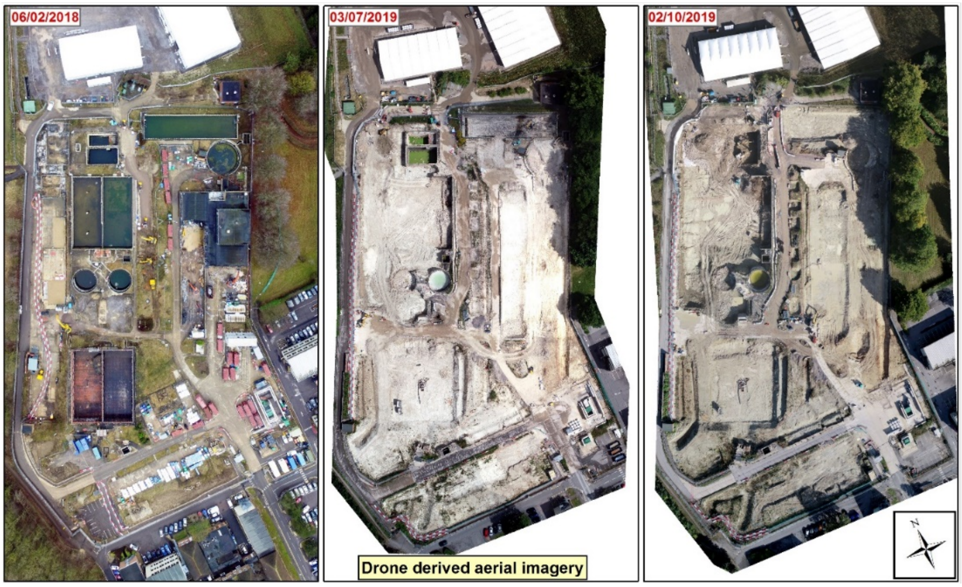


FIG. A-13. Drone-derived aerial imagery showing the progress of remediation of the Liquid Effluent Treatment Plant at the Harwell site, United Kingdom. (Photos: Magnox Ltd)

85. In February 2019, Energy Resources of Australia, the Ranger uranium mine (Figure A-14) operator, finalized the Ranger Closure Feasibility Study, which provides a detailed rehabilitation schedule and associated cost estimate of AUD 830 million. Progressive rehabilitation has been under way since 2012, and, to date, significant milestones include the backfill of Pit 1 with tailings and waste rock, the decommissioning of an underground exploration decline, the dredging of tailings from the tailings storage facility to Pit 3, the construction and operation of a brine concentrator to treat process water and the commencement of revegetation. Under current approvals, mining and processing activities must cease by January 2021, and final rehabilitation must be completed by January 2026. A key rehabilitation objective is to bring the ecosystem of the site into line with that of the surrounding environment so that it can eventually be incorporated into the Kakadu National Park.

FIG. A-14. Ranger uranium mine site. (Photo: Energy Resources of Australia)

86. In the United States of America, the Environmental Protection Agency has nearly completed the activities to remediate a key feature of the Mississippi Phosphates Corporation site. At a cost of approximately USD 72 million, a unique cover system has been installed over the West Gypsum Stack, covering an area of around 235 acres. The basis of the cover system is a linear low-density polyethylene material that will limit rain infiltration and reduce the leaching of both radiological and chemical contaminants from the stack. The cover system enables permanent closure of the site while minimizing risks to people and the environment. The site, which began operations in the 1950s, had produced diammonium phosphate fertilizer. Operations ceased in 2014 owing to bankruptcy, leaving more than 700 million gallons of acidic contaminated wastewater stored at the facility and phosphogypsum waste disposed of in two stacks. A stack is a mound created from slurried phosphogypsum and gypsum.

87. In December 2019, Italy made significant progress in the remediation of the Trisaia site by completing the removal of a reinforced concrete structure containing radioactive waste. Built in the late 1960s, the vertical, prism-shaped structure was located 6.5 metres under ground, with a mass of about 130 tonnes and a volume of 54 cubic meters.

88. In 2019, the Chornobyl NPP cooling pond decommissioning project was completed. The project commenced in 2014 following the completion of several radiological and ecological studies and the development of a feasibility study and environmental impact assessment supported by the Agency. These studies recommended that the water supply to the cooling ponds should be stopped to allow the drawdown of the ponds. It was also recommended that, during the drawdown, ecological and radiological monitoring should occur to ensure the continued safety of people and the environment. The monitoring data has concluded that ecological changes and redistribution of radiological contaminants has broadly occurred as predicted by the feasibility study. The decommissioning has significantly decreased operational costs for the cooling pond area and reduced flood risks in the surrounding area. The ecological status of the site continues to improve each year, and health and safety is maintained through the restrictions in place for the exclusion zone (Figure A-15).

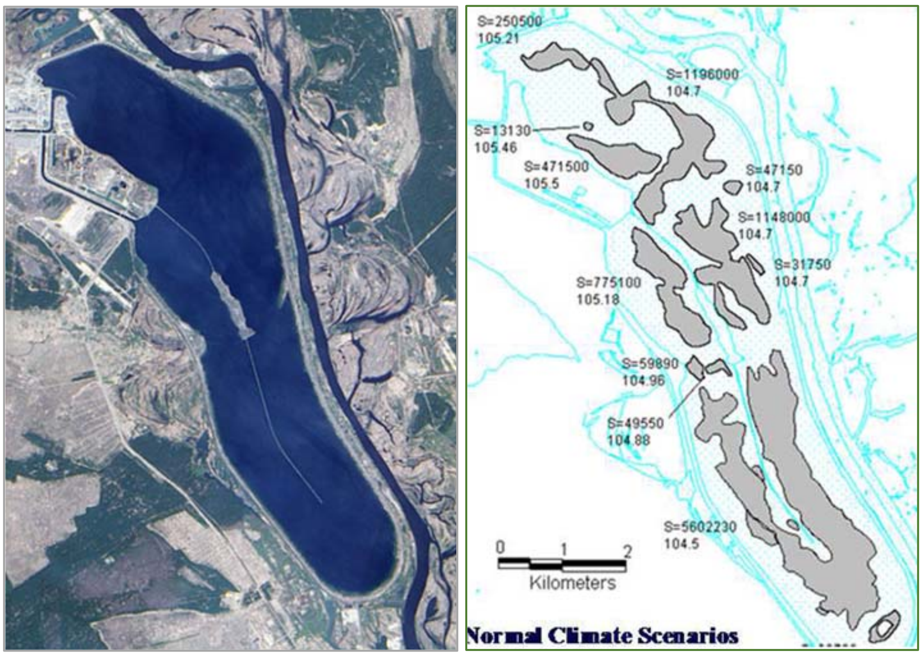


FIG. A-15. Left: Aerial image of the Chornobyl NPP cooling pond prior to decommissioning. Right: Computer simulations showing the remaining water bodies after decommissioning. (Photo: SSE Chornobyl NPP)

A.4.3. Radioactive Waste Management

Management of disused sealed radioactive sources

End-of-life management options for disused sealed radioactive sources (DSRSs) are actively being explored, including co-disposal with other waste at suitable facilities. Borehole disposal projects are progressing in several countries, including Ghana and Malaysia. The licence for the borehole disposal project in Malaysia was issued in July 2019 by the regulatory body to the Malaysian Nuclear Agency.

89. The commissioning of the Mobile Tool Kit Facility for the conditioning of lower category DSRSs (Categories 3 to 5) in preparation for the disposal project was completed in June 2019 and shipped to Malaysia in September 2019. The borehole drilling operations are expected to begin in early 2020.

90. In 2019, Ghana successfully completed the characterization and conditioning of Category 3–5 DSRSs, which have been moved to a centralized storage facility pending emplacement in a borehole disposal system at a Ghana Atomic Energy Commission site.

91. Several successful operations have been conducted in 2019 to remove DSRSs from user facilities and bring them under safe and secure storage conditions. The last remaining Category 1 DSRS was removed from North Macedonia, while two DSRSs (Category 1 and 2) were removed from Albania.

92. In several other Member States, including Croatia, Cyprus, Jordan, Nepal, Nicaragua, Slovenia and Tunisia, the removal of Category 1 and 2 sources has been initiated.

93. Operations to condition DSRSs were completed in Curaçao, with local personnel receiving appropriate classroom and hands-on training on DSRS management.

94. National inventories of DSRSs, in addition to sealed sources in use, were established and/or updated in Grenada, Haiti, Papua New Guinea and Saint Vincent and the Grenadines, as well as in Curaçao.

95. Several Member States, including Barbados, Guyana, Kenya and Malaysia, increased their capacity for orphan source search and recovery through national or regional training.

96. The International Catalogue of Sealed Radioactive Sources and Devices is undergoing an extensive software update with inputs provided by Member States and internal stakeholders. Efforts to add more details on sources and devices were ongoing in 2019.

Predisposal

97. The Advanced Mixed Waste Treatment Project (AMWTP) located at the US Department of Energy's (DOE's) Idaho National Laboratory (INL) completed its mission in November 2019. First commissioned in 2003, it prepared over 65 000 m³ of transuranic intermediate level waste (ILW) for disposal at the Waste Isolation Pilot Plant (WIPP) in New Mexico, United States of America. The AMWTP used a combination of conventional and high-tech retrieval, characterization and treatment technologies, including robotics, to process the ILW from the INL and from 15 other DOE sites.

98. In July 2019 processing work commenced at the Chornobyl NPP liquid waste processing plant. As of September 2019, 120 waste packages had been prepared for disposal. The design capacity of the plant is 42 waste packages (200 litres each) per day. The first 120 packages have been transferred to the Vector production complex for disposal.

99. In Finland, the cornerstone for the spent nuclear fuel encapsulation plant was laid, and construction began in September 2019. The encapsulation plant will prepare spent nuclear fuel for final disposal. The encapsulation plant is a key component in the implementation of the Finnish disposal programme and links with the geological disposal facility under construction in Olkiluoto, Finland (Figure A-16).

FIG A-16. Construction of Posiva's spent nuclear fuel encapsulation plant. (Photo: Posiva)

100. In Georgia, a site was proposed for the siting of an interim storage facility and a processing facility to manage legacy waste in the country. The legacy waste, arising from activities between the 1950s and 1980s, include radioactive sources, radioactive materials, and other items contaminated by radioactive substances. The European Union provided funding for the design of the planned processing and interim storage facilities for the site. The Swedish Radiation Safety Authority (SSM), in collaboration with the Swedish International Development Cooperation Agency (SIDA), coordinates international procurements supporting the project and provides assistance to the Georgian government. In Moldova, a project for the management of radioactive wastes from a RADON-type facility is advancing. A detailed plan and supporting technical documents for retrieval, radioactive waste management and decontamination of the facility are currently under development.

101. In September 2019, the United Kingdom published an integrated radioactive waste management strategy, covering all the radioactive waste arising within the estate of the Nuclear Decommissioning Authority, encompassing 17 sites. The relevant activities include NPPs, spent fuel reprocessing facilities, research establishments and disposal sites. Also, the decontamination of the bunkers containing plutonium contaminated material (PCM) at the Low Level Waste Repository site was completed, following six years of work. The work included the repackaging and removal of PCM to safe storage facilities at Sellafield, United Kingdom.

Disposal

102. Disposal facilities for low level waste (LLW) and ILW have been operational throughout 2019 in many Member States. These include trench disposal for very low level waste (e.g. France, Spain, Sweden) or for LLW in arid areas (e.g. South Africa, United States of America); near surface engineered facilities for LLW (e.g. in China, Czech Republic, France, India, Japan, Russian Federation, Slovakia, Spain, United Kingdom); and engineered facilities for low and intermediate level waste (LILW) sited in

geological formations at a range of depths (e.g. Czech Republic, Finland, Germany, Hungary, Republic of Korea, Norway, Russian Federation, United States of America).

103. Furthermore, disposal facilities for LLW are under construction at the National Disposal Facility (NDF) at the Radiana site near Kozloduy NPP in Bulgaria and at the Anarak nuclear waste repository site in the Islamic Republic of Iran. Phase 1 of construction of the NDF is expected to be completed at the end of July 2021, and disposal operations are expected to begin after commissioning in 2023 (Figure A-17). In the Islamic Republic of Iran, construction of the operational support facilities is under way and expected to be completed in 2022 with an operational licence planned for 2025.

FIG A-17. Construction of the NDF at the Radiana site near Kozloduy NPP showing part of the administration complex (left), the waste reception and buffer storage building (right), and the loess-cement foundation of Disposal Platform 1 (far right).

104. In Lithuania, the construction tender for a near surface disposal facility at Ignalina NPP was announced in March 2019 with construction planned to begin in 2020. In Belgium, the licence application for the Dessel facility was submitted in February 2019.

105. In September 2019, negotiations between Croatia and Slovenia on a potential joint LLW repository concluded with an agreement to construct and operate two separate national repositories. Slovenia will continue preparation of the licence application for construction of the Vrbina repository located near the Krško NPP, and Croatia will pursue a concrete vault type repository at Čerkezovac.

106. The technical design and associated safety assessment for an LLW repository located at El Tuwaitha, Iraq was completed in the summer of 2019 and submitted to the Iraqi Ministry of Science and Technology as operator and to the Ministry of Environment. The technical design was funded by the European Commission.

107. In Pakistan, a site for a near surface disposal facility for LLW was selected at the Potwar Plateau, and the initial design work was initiated.

108. In Germany, construction work on the Konrad repository for ILW is continuing, with excavation works for the shaft 2 waste transfer station completed in June 2019.

109. Significant progress is being made in the disposal of high level waste (HLW) in several Member States. Finland is constructing a deep geological facility, Sweden is awaiting a final decision on its licence application and France is finalizing the licence application for the Cigéo facility. In Finland, construction contracts have been awarded for the first two waste transportation tunnels and

first five deposition tunnels, where the encapsulated spent nuclear fuel will be disposed of. Tunnelling work was set to begin by early 2020 and last for about two and a half years. The regulator approved the Swedish Nuclear Fuel and Waste Management Company's (SKB's) supplemental information providing responses to the questions raised by the Land and Environmental Court as part of the licensing process for a deep geologic repository. The final decision will rest with the Swedish government. In France, work on the Cigéo project for a deep geologic repository for HLW in Callovo-Oxfordian claystone is progressing towards an anticipated 2020 licence application submission.

110. Significant programmatic milestones in HLW disposal were also achieved in other Member States. In China, final authorization was given on 6 May 2019 for the construction of an underground research laboratory (URL) in the Beishan area of the Gobi Desert (granitic formation). The URL is intended to investigate the local granitic rock's suitability for hosting a deep geologic repository for HLW. It is planned to be constructed at a depth of 560 metres and will be open to requests from other Member States interested in conducting and participating in research. In addition, work is progressing on identifying a site for a potential repository in a clay formation in China. The first project was completed at the end of 2018 and accepted by the China Atomic Energy Authority in October 2019. Two potential sites for further investigation have been identified.

111. In the United Kingdom, the new siting programme was launched in England (December 2018) and Wales (January 2019) for a deep geologic repository for higher activity radioactive waste. Currently, Radioactive Waste Management (RWM) Ltd. (the operator) is actively engaging with potentially interested communities and the wider public to raise awareness, answer questions and discuss the hosting of a geological disposal facility. RWM has carried out a high-level review of geological data relevant to the safety of a geological disposal facility in order to inform initial discussions.

112. In the United States of America, a contract for a new utility shaft at the WIPP was awarded by the DOE Carlsbad Field Office and the Nuclear Waste Partnership. The new shaft is a key component in efforts to restore full capacity operations at the LILW repository in Carlsbad, New Mexico, following its reopening on 9 January 2017 and the acceptance of a first shipment on 10 April 2017.

B. Advanced Fission and Fusion

B.1. Advanced Fission

113. Advanced nuclear reactors and their applications are gaining momentum in every region of the world, as they are seen as nuclear energy systems able to contribute to the global transition towards more sustainable, affordable and reliable energy systems. They are also more suitable to be integrated in future carbon-free power systems, which will be characterized by large shares of variable power generation sources. In particular, one promising technology is regarding SMRs, which can meet clean baseload power needs whilst operating flexibly to accommodate variable renewables and respond to demand. They are also particularly suitable for non-electric applications of nuclear power such as desalination, hydrogen production, district heating and cooling as well as several energy-intensive industrial applications.

B.1.1. Water Cooled Reactors

114. Several designs of water cooled reactors (WCRs) with evolutionary and innovative technologies are now under construction, commissioning or operation worldwide. Many of the lessons learned from the past 50 years of WCR operation continue to be applied. Recent advances in WCR technology include

improvements in existing designs and the development of new designs, sharing the common goals of enhanced safety, a more efficient resource use and better economics. In most of the evolutionary concepts, safety systems have passive features that do not rely on electric power and include larger water inventories, allowing for coping times of days instead of hours in the event of unplanned conditions, such as an extended station blackout. Another important aspect of WCR development is the design, testing and construction of small modular, factory-built integral pressurized water reactors (PWRs) (see Section B2.2).

115. In Argentina, a CANDU 6 heavy water reactor (HWR) is planned and an HPR1000 PWR is being considered. Argentina also plans to develop all fuel production capabilities. Partnering options are being pursued to restart and complete the construction for commercial operation of Brazil's Angra 3 NPP by 2026.

116. In Canada, the refurbishment of the Darlington and Bruce NPPs in Ontario is expected to be completed by 2032, with a total investment of CAD $26 billion, and Pickering NPP is due to shut down by 2025. CANDU new builds are under consideration in Argentina, China, Romania and the United Kingdom.

117. China continues to have the most ambitious national advanced light water reactor development programme. The government has restarted the approval process for new plants and is considering the implementation of carbon pricing. All new plants will use fully digital operation, including for instrumentation and control and for reactor protection systems. The nine NPP units at Qinshan have maintained a capacity factor of ~90% since 2013. With regard to HWRs in China, the focus is on long term operation (LTO) and pressure tube life extension issues, as well as on preparation for retubing.

118. India is projected to account for 25% of world energy demand growth from now until 2040. The expansion of the current fleet relies on Indian 700-MW(e) class HWRs and imported PWR technologies. The Bhabha Atomic Research Centre is developing a 4-loop ~900 MW(e) advanced PWR (Indian Pressurized Water Reactor) along with dedicated test facilities. The manufacturing supply chain in India has improved.

119. In Pakistan, a new relicensing application for the period 2019–2024 has been submitted for the HWR at Karachi NPP.

120. The Korea Electric Power Corporation is engaged in PWR development for export markets, with the addition of a 1 GW(e) advanced PWR and iPOWER, an innovative 1250 MW(e) fully passive PWR, to its existing APR1400 reactor. HWR R&D activities are mainly related to LTO, fuel channel life management (FCLM) and retubing, as well as severe accident management guidelines. Wolsung Units 2,3 and 4 could be the first CANDU 6 reactors to take advantage of FCLM to extend the design life of their pressure tubes.

121. In Romania, Cernavodă Unit 1 refurbishment is planned to start in 2026, following the extension of pressure tube life beyond the 210 000-hour design life.

122. The Russian Federation continued to focus on lifetime extensions and uprating of 4–10% in its 20 operating VVERs. The lifetime extensions are based on technical and economic factors, leading to 11–30 years of extended life. Rosatom received orders for 36 VVER units to be supplied worldwide, currently at different stages of negotiations, planning, and construction.

123. A total of 98 nuclear reactors were operating at 60 nuclear power plants in 30 states of the United States of America, providing about one fifth of the country's total annual electricity. The average age of these nuclear reactors is about 38 years. The oldest operating nuclear power reactor, Nine Mile Point Unit 1 in New York, began commercial operation in December 1969. The newest reactor, which came online in 2016, is Watts Bar Unit 2. The two new reactors under construction — Vogtle Units 3

and 4, based on Westinghouse AP1000 technology, in Georgia — are expected to become operational between 2021 and 2022.

124. Canada, China, Japan, the Russian Federation and the European Union are the signatories of the System Arrangement to participate in joint R&D in developing SCWR concepts (Figures B-1 and B-2). The main purpose of the SCWR is to generate electricity efficiently, economically and safely. The majority of SCWR plants are developed for power generation of higher than 1000 MW(e) at operating pressures of about 25 MPa and reactor outlet temperatures from 500°C to 625°C. As a consequence, SCWRs could generate electricity with thermal efficiencies ranging from 43% to 48%, which is significantly higher than those of the current fleet of nuclear reactor systems. The high core outlet temperature of SCWRs facilitates cogeneration, including hydrogen production, heating and steam production.

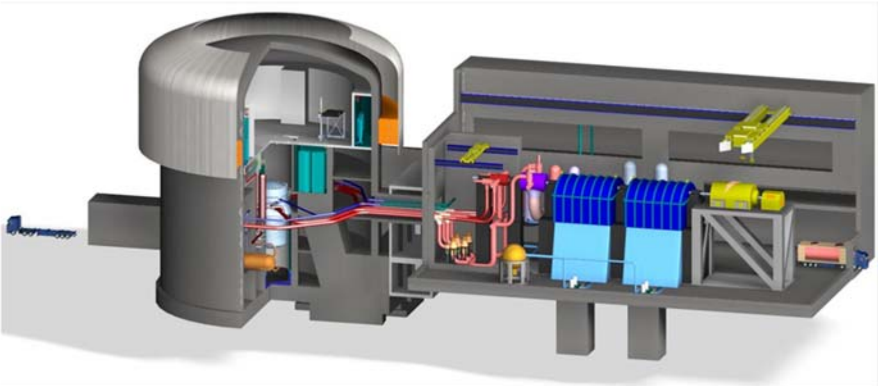


FIG. B-1. Canadian SCWR design: reactor buildings and the turbine building. (Source: IAEA)

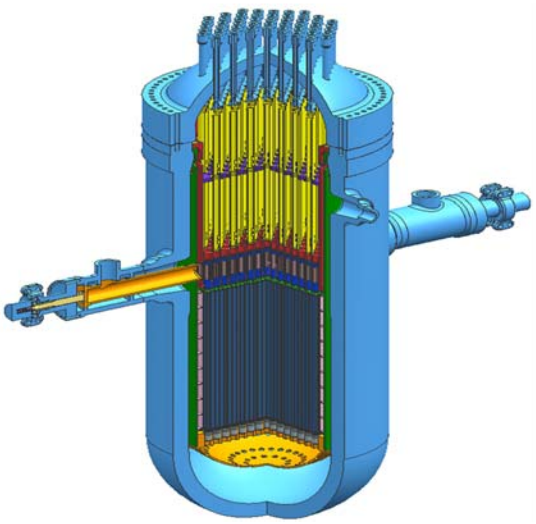


FIG. B-2. Reactor core concept of the Chinese SCWR design. (Source: IAEA)

B.2. Fast Neutron Systems

125. The first reactor that produced electricity was Experimental Breeder Reactor-I in 1951 in the United States of America. The 100 kW(e) reactor was cooled by sodium-potassium alloy, a liquid metal. Since then, the most mature fast reactor technology, the sodium cooled fast reactor (SFR), has been developed around the world, reaching more than 400 reactor-years of operational experience through experimental, prototype, demonstration and commercial units in several countries, including China, France, Germany, India, Japan, the Russian Federation, the United Kingdom and the United States of America. Several innovative (Generation IV) sodium cooled, lead and lead–bismuth eutectic cooled fast reactors (LFRs) as well as gas cooled fast reactors (GFRs) are under development at national and international levels. The molten salt fast reactor is also being developed as a long-term option.

126. In the People's Republic of China, the innovative demonstration SFR, CFR-600, is in design and construction, with plans to start operation in 2025. Several institutes are developing lead and lead–bismuth cooled SMRs, including accelerator-driven systems (ADS). China's first lead–bismuth alloy zero power subcritical reactor, Qixing (Venus) III, achieved its first criticality on 9 October 2019 (Figure B-3). The zero power ADS will be used for research on transforming long lived radioactive waste into short lived waste.

FIG. B-3. Qixing (Venus) III reaches first criticality. (Photo: China Institute of Atomic Energy)

127. According to India's three-stage nuclear power programme, construction of the 500 MW(e) Prototype Fast Breeder Reactor (PFBR) has reached its final stage; the reactor is under advanced commissioning and is expected to reach first criticality in 2020. The PFBR will succeed a small, 12-MW(e) test reactor built by the Indira Gandhi Centre for Atomic Research in 1985.Two more fast breeder reactors are planned at the same site in Kalpakkam.

128. Since 1980, the Russian Federation has operated BN-600, an industrial prototype SFR. Another SFR, the 880 MW(e) BN-800 has been in commercial operation since 2016. In August 2019, the hydraulic tests of the reactor vessel were completed at the Multipurpose Fast Research Reactor (MBIR) (Figure B-4), which will replace the experimental BOR-60 reactor in 2024. The lead cooled BREST-OD-300 and lead–bismuth cooled SVBR-100 are in the licensing process.

FIG. B-4. MBIR facility.

129. The French Government decided to extend its R&D programme on SFR technology and to defer plans to build a prototype Generation IV SFR (Astrid). Belgium has decided to construct MYRRHA, a lead–bismuth cooled reactor that can operate in subcritical and critical modes as an ADS; the first facility is expected to be operational by the end of 2024. The design of the Swedish Advanced Lead Reactor (SEALER) 55 MW(e) SEALER-UK plant (Figure B-5) was submitted to the UK Department for Business, Energy and Industrial Strategy for review. Other fast reactor designs under development in Europe are ALFRED, the European demonstration of a Generation IV LFR with SMR-type features, which Romania has offered to build at Mioveni, and ALLEGRO, an experimental GFR.

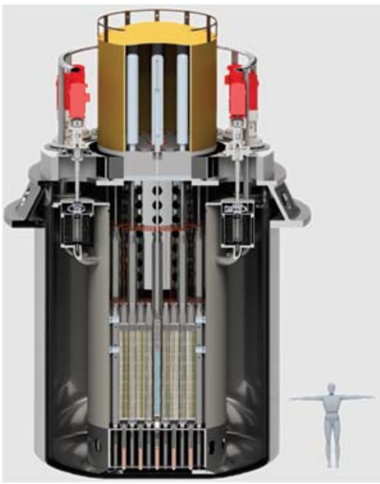


FIG. B-5. 55 MW(e) SEALER-UK LFR design.

130. In the United States of America, TerraPower has completed the core conceptual design of the ‘breed-and-burn’ travelling wave reactor. Westinghouse is developing an innovative lead cooled 450 MW(e) small modular reactor. In February 2019, the U.S. Department of Energy announced plans to build a Versatile Test Reactor (VTR) for studies related to irradiation under very high energy neutron fluxes.

131. The IAEA supports its Member States in developing fast reactor technology by organizing and conducting coordinated research projects (CRPs), workshops and topical studies. In particular two key CRPs which contribute to the advancement of the FR technology, are being carried out: the first one

concerns a neutronics benchmark of the China Experimental Fast Reactor start-up tests and the second one a multiphysics analysis of an unprotected loss-of-flow experiment at the US fast flux test facility (FFTF).

B.2.1. Gas Cooled Reactors

132. Despite the long history of gas cooled reactors, the only ones remaining in commercial operation are the 14 advanced gas cooled reactors in the United Kingdom. Some of these reactors are expected to be operating into the early 2030s, with the lifetime primarily limited by nuclear graphite behaviour.

133. The gas cooled reactors under development for near term deployment are all small modular high temperature gas cooled reactors (HTGRs). These designs rely on inherent safety characteristics and eliminate most active engineered safety systems; the radioactivity confinement is guaranteed by the coated particle fuel. These reactors use helium as a coolant and graphite as moderator and operate at higher temperatures (at or above 700°C) with respect to current NPPs, increasing electricity generation efficiency and potentially serving a large process heat market.

134. In Canada, several SMR pre-licensing activities are taking place that include four HTGR designs. The Canadian Nuclear Safety Commission (CNSC) has received the first licence application for a small modular HTGR. The application from Global First Power, with support from Ontario Power Generation and the Ultra Safe Nuclear Corporation, proposes the deployment of an HTGR-type Micro Modular Reactor plant at Chalk River in Ontario.

135. The High Temperature Reactor–Pebble Bed Module (HTR-PM) in China is scheduled for commercial operation in 2020. This full-scale demonstration plant of 210 MW(e) consists of two reactor units coupled to a single power turbine. For future deployment, the same reactor and steam generator configuration (six units) will be coupled to a single 650 MW(e) power turbine in the commercial HTR-PM600 design, with several feasibility studies for deployment in China under consideration. The HTR-10 test reactor renewal project has been completed and additional safety demonstration tests are planned.

136. In Japan, permission to restart the 30 MW(th) High Temperature Engineering Test Reactor is expected in the next year. Additional safety demonstrations, the coupling of a helium power turbine and the demonstration of coupled high-temperature nuclear hydrogen production are envisaged in the next few years. Japan is also actively pursuing the international deployment of SMRs based on Japan's HTGR technology through international partnerships.

137. In the United States of America, activities concerning fuel qualification (irradiation and heat-up tests) are ongoing and confirm the excellent fission product retention of tristructural isotropic (TRISO) fuel. General design requirements have been published for advanced reactors and HTGRs and should facilitate a more appropriate licensing framework in the country. Some material qualification is continuing, while test facilities to illustrate passive safety characteristics are receiving support. The 75 MW(e) XE-100 pebble bed design and pre-licensing activities are still in progress.

138. Many embarking countries are considering the deployment of HTGRs. Saudi Arabia included HTGR deployment in the National Atomic Energy Project for industrial process heat applications in the petro-chemical industry. Jordan included HTGRs in its feasibility studies for the deployment of SMRs for electricity production, desalination and process heat, and Poland is still pursuing plans to deploy HTGRs for industrial heat applications. In Indonesia, the construction of the 10 MW(th) pebble bed experimental power reactor is no longer pursued, but R&D continues and a project with China to develop a commercial-size reactor is under way.

139. Activities related to HTGR deployment are continuing in the European Commission as part of the GEMINI+ programme, to be completed in 2020. Technology development is ongoing in the Republic of Korea and the Russian Federation. In South Africa the R&D work on a new AHTR-100 pebble bed concept has been discontinued.

140. The Agency develops and maintains the Nuclear Graphite Knowledge Base on irradiated graphite, which includes historical records and knowledge to facilitate the future deployment of graphite moderated reactors.

141. Additionally, the Agency CRPs on uncertainty in reactor analysis, on the development of safety design criteria for modular HTGRs and on the application of HTGR heat for mineral extraction for a more sustainable and clean product have all been concluded and the final reports are under development.

142. Based on increasing Member State interest and requests from Member States, the Agency has conducted limited activities on molten salt reactors (MSR). A document on the status of MSR technology is under development based on the R&D activities in Member States. Some of the areas of common interest with gas cooled reactors include high temperature materials, graphite behaviour and coated particle fuel (used in molten salt cooled reactor designs).

B.2.2. Small and Medium Sized or Modular Reactors

143. The technology development of SMRs for immediate and near term deployment is progressing globally. At the International Conference on Climate Change and the Role of Nuclear Power, organized by the Agency in October 2019, the participating Member States expressed that, with a typical output of 300 MW(e), SMRs could be the most effective source of CO2-free electricity to supersede ageing fossil fuel powered plants. Furthermore, with the higher share of intermittent renewable energy on all continents, SMRs are considered indispensable to providing both baseload and flexible operations in synergy with renewables to ensure the security of energy supply.

144. The major challenges for the large-scale deployment of SMRs are to demonstrate that the modularity will achieve the promised lower levelized costs through economy of serial production, and whether design simplification and short time of construction lead to easier and more affordable financing schemes. Gaps between technology holder countries and embarking countries with developing economies remain wide with regard to achieving a common understanding of the requirements and criteria of feasible SMR design and technology. Therefore, it is of paramount importance that top-tier generic user requirements for SMRs, addressing different policies, are developed.

145. More than 50 SMR designs and concepts are in different stages of development for various applications.

146. Construction of two new NPPs with SMRs in China and the Russian Federation has been completed and start-up commissioning is under way to prepare for connection to the electricity grid for potential commercial operation in 2020.

147. In Argentina, the CAREM-25 prototype module is in the advanced stage of construction at the Néstor Carlos Kirchner NPP site and aims for fuel loading and start-up commissioning in September 2022. The prototype is designed to produce 100 MW(th) and 34 MW(e) gross. This integral-PWR type SMR will operate in full natural circulation mode and adopt passive safety features. CAREM-25 was developed using domestic technology and at least 70% of the components and related services were sourced from Argentinean companies.

148. Canada's SMR Roadmap foresees possible applications for on- and off-grid replacement of fossil and diesel generation plants, including in the oil and mining industries. Presently, 12 SMR

designers/vendors are working with the CNSC, and a site preparation licence is being sought by Global First Power for an SMR at Chalk River Laboratories.

149. In China, the construction of the HTR-PM, which will produce 210 MW(e) from two reactor modules connected to a steam turbine generator system, has been completed and is under commissioning. More detail on HTR-PM is reported in section B.2.1. China has also launched a construction project for the ACP100, also known as Linglong One, a 125 MW(e) integral-PWR designed as a multipurpose small power reactor at Changjiang in Hainan province. The duration of construction is estimated at five years, with start-up commissioning foreseen in 2025 for generating electricity, industrial process heat and desalinated water. Regarding marine-based SMRs with PWR technology, China has been performing technology development for three floating SMR designs, namely the ACPR50S, ACP100S and CAP-F.

150. During the 63rd regular session of the Agency's General Conference in September 2019, a French national consortium, comprising the French Alternative Energies and Atomic Energy Commission, Électricité de France and TechnicAtome, announced the launch of NUWARD, a 170 MW(e) integral-PWR type SMR with forced convection and advanced safety systems for potential deployment in foreign markets in the early 2030s.

151. The Republic of Korea and Saudi Arabia have joined forces to complete the detailed design of SMART, a 110 MW(e) (365 MW(th)) integral-PWR, of which the two countries have co-ownership. It will be constructed in Saudi Arabia and used for cogeneration of electricity and seawater desalination. The new optimized design has increased power and incorporated full passive safety features. When completed, the design will be submitted for certification in the Republic of Korea in parallel with a licensing application in Saudi Arabia.

152. In the Russian Federation, the Akademik Lomonosov floating NPP (FNPP) (Figure B-6), with a KLT-40S compact PWR-type SMR, arrived at Pevek in the Chukotka region in mid-September, having been towed 4900 km from the fuelling pier at Murmansk. The FNPP, which received an operating licence in July 2019 and was connected to the grid in December 2019, has two 35 MW(e) KLT40S reactor modules, together generating up to 70 MW(e) and 50 gigacalories of heat per hour, which is sufficient to supply power to a town of about 100 000 residents. The purpose of the FNPP is to replace the decommissioned Bilibino NPP and ageing coal-fired power stations, to power a mining complex and to supply electricity to oil rigs in the Arctic. The FNPP can also produce desalinated water.

FIG. B-6. The Akademik Lomonosov FNPP. (Photo: Rosatom)

153. In the Russian Federation, the RITM-200, a 50 MW(e) integral-PWR SMR, is being considered for construction in the Republic of Sakha (Yakutia). It was originally designed and deployed for nuclear icebreaker ships but the land-based, on-the-grid version is being developed for near term deployment.

154. In 2019, the United Kingdom continued to work on developing technology for the UK SMR, a three-loop PWR-based SMR design capable of generating 450 MW of electricity, with the aim of obtaining design approval for domestic deployment in the 2030s.

155. In the United States of America, NuScale started design certification review with the Nuclear Regulatory Commission (NRC) in the first quarter of 2017 and is estimated to receive design certification by the end of 2022. The NuScale Power Module (NPM) is an integral-PWR with natural circulation and full passive safety features. A 60 MW(e) NPM provides power in increments that can be scaled to 720 MW(e) gross in a single NPP. A 12-module configuration is the current reference plant size for design and licensing activities, and the plant is expected to start operation by the mid-2020s at the Idaho National Laboratory.

156. Most of the water cooled based SMRs are either compact, integral or loop-type PWRs. However, Japan and the United States of America have strengthened design and technology development projects for the BWRX-300, a natural circulation boiling water reactor (BWR) designed to produce 300 MW(e) and with design simplification and passive safety features. This direct steam cycle BWR-type SMR design is being developed based on the NRC-licensed, 1520 MW(e) ESBWR.

157. Throughout 2019, a subset of SMRs known as micro modular reactors also moved forward in several countries, including Canada and the United States of America. An example is the Micro Modular Reactor (MMR), with a high temperature gas and prismatic block reactor core being designed to produce an approximate capacity of 5 MW(e). MMR has been submitted for vendor design review to the CNSC. There is not yet global consensus on the definition and power range of micro modular reactors. In the United States of America, an integral PWR design called SMR-160 has also been undergoing design assessment.

158. In 2019, the Agency initiated a new project aimed at supporting Member States interested in carbon-free hybrid energy systems integrating variable renewable energy sources, SMRs, energy storage and non-electric applications.

B.2.3. International Initiatives on Innovative Nuclear Energy Systems

159. Established by the Agency in 2000, INPRO brings together technology developers, suppliers and customers to consider international and national actions for achieving desired innovations in nuclear reactors and fuel cycles for the long term sustainability of nuclear power. INPRO currently has 42 members — 41 Agency Member States and the European Commission — and provides an international forum to consider issues of interest and policy coordination, and to allow technology holders and users to collaborate and communicate their needs and interests in the relevant areas.

160. To promote a global vision of sustainable nuclear energy development in the 21st century, the nuclear energy system scenario modelling, analysis and roadmapping tools documents are in the final stages of publication. Workshops and training events using these tools were conducted in Mexico and the Russian Federation in 2019 and one is planned in Thailand in 2020. An INPRO Dialogue Forum on "Opportunities and Challenges in Small Modular Reactors" was also held in the Republic of Korea in 2019. Such dialogue forums allow INPRO to engage Member States on evolving issues in nuclear energy system sustainability.

B.2.4. Non-electric Applications of Nuclear Power

> Whether in cogeneration or integrated with other renewable energy resources, the use of nuclear energy for non-electric applications can penetrate a wide range of sectors, including: water desalination, transportation (e.g. hydrogen production for fuel cell-driven vehicles), residential (district heating and cooling) and industry (petrochemical, steel and synthetic fuel production industries).

161. In 2019, a total of 74 operational nuclear power reactors (15 in Asia and 59 in Europe) were used worldwide to generate 2122.92 GW·h of electrical equivalent heat to support non-electrical applications of nuclear energy. Of these reactors, 11 supported desalination (using 31.4 GW·h), 58 supported district heating (1979.27 GW·h) and 33 supported industrial process heat applications (1313.86 GW·h). Interest in non-electric applications of nuclear energy continues to grow worldwide. The use of nuclear energy to serve these sectors provides a sustainable route to ensure energy security and combat climate change. The recovery and use of waste heat from NPPs (i.e. heat rejected by an NPP's condenser) for non-electric applications can lead to an overall increase in the plant's thermal efficiency and can reduce the environmental impact of this heat when discharged into rivers or other water bodies. Cogeneration using recovered waste heat can offset a significant part of nuclear power generation costs. For example, the waste heat from HTGRs could be used in seawater desalination, resulting in cost credits against the price of the produced water from desalination plants driven by gas or oil-fired power plants. Indeed, NPPs can also provide adequate, cost-effective process heat or steam. This can be used for several other applications, including district heating and cooling.

162. In China, it was announced in November 2019 that Haiyang is the first city in China to be supplied with process heat from the two AP1000 units at Haiyang NPP. According to Shandong Nuclear Power Company (SDNPC), the owner of Haiyang NPP, the project will expand to cover the entire city of Haiyang by 2021. SDNPC estimates that these two units can meet the future demand of district heating to as much as 200 million square meters of housing, saving 6.6 million tonnes of coal each year. Currently, technology solutions are available for large amounts of heat (~GW) to be transported over long distances (~100 km) with minimal heat losses.

163. Seawater desalination using heat discharged from condensers of NPPs or heat extracted as low-quality process steam from late stages of a low-pressure turbine and fed to a multiple effect distillation desalination system is seen as a viable option when considering NPP projects. It supports the water needs of a power plant through its life cycle: construction, operation and decommissioning. Advancements in desalination-related technologies such as low temperature operating systems, waste heat recovery systems, efficient energy and process systems, and innovative process optimization, increase the potential of nuclear desalination. Integrated hybrid thermal and membrane desalination is seen as the optimal option for nuclear desalination. This could reduce energy consumption, the volume of seawater intake and the cost of outfall. Several Member States, including Brazil, China, Egypt, India, Jordan, Pakistan and Saudi Arabia, have expressed or renewed interest in nuclear desalination.

164. The use of nuclear energy for hydrogen production can enable the flexible fleet of nuclear reactors to play a key role in the future hydrogen economy and climate change mitigation. Currently operating NPPs can produce hydrogen through advanced low temperature water electrolysis. The economics of this process could be improved by using electricity generated off-peak. Several other hydrogen production technologies have progressed in recent years, including high temperature electrolysis and thermochemical or electrothermo-chemical hydrogen production cycles. These technologies can be integrated into future high temperature reactor designs.

B.3. Fusion

165. Substantial progress has been made in the ITER construction, with more than 73% of the civil work finalized (Figure B-7). The revised construction schedule, dated 2016, has been recently reconfirmed, keeping intact the originally agreed deadline for production of the first plasma by the end of 2025. The tokamak building is ready for the installation of the cryostat base, planned for March 2020, and the work around this component will last for more than four years. ITER is expected to start operation at full fusion power in 2035.

FIG. B-7. Photos of the ITER construction site in April 2014 (left) and in October 2019 (right). (Photo: ITER)

166. In June 2019, the IAEA and the ITER Organization strengthened already longstanding cooperation through the signature of Practical Arrangements. Under the new Arrangements, the ITER Organization will share its experience related to nuclear fusion safety and radiation protection with the IAEA and its 171 Member States. The two organizations will also implement educational initiatives on plasma physics and fusion engineering, coordinate public outreach activities, and cooperate in knowledge management and human resources development.

167. Another important milestone in the development of fusion as a future source of energy is the construction of the JT-60SA machine (Figure B-8), a superconducting tokamak being built in Naka, Japan, as an international collaboration between Europe and Japan.

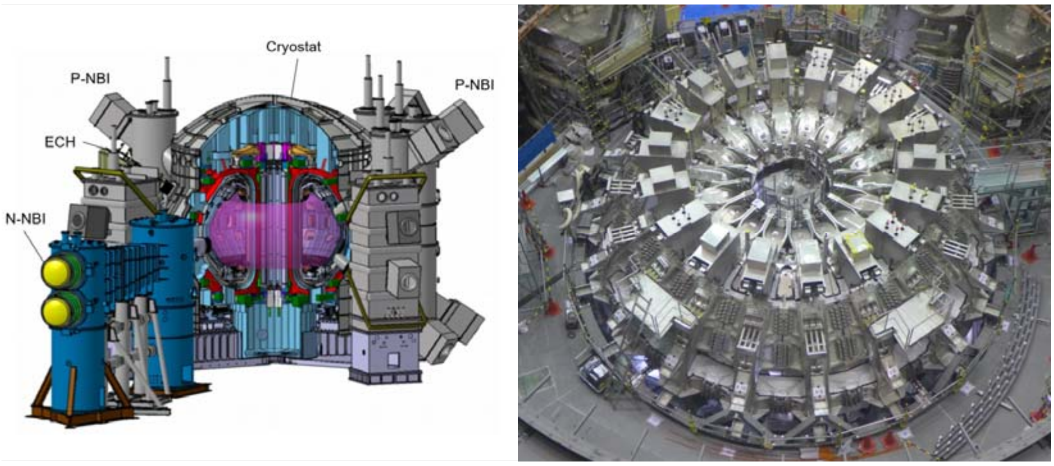


FIG. B-8. Schematic representation of the JT-60SA (left) with a photo of the close-to-completion torus assembly. (Source: P. Barabaschi et al., presented at the 2018 IAEA Fusion Energy Conference)

168. With the commissioning of the JT-60SA expected in 2020, it is expected to be operational five years prior to ITER, so that its experiments will support the commissioning and operation of ITER. Some of the research topics that JT-60SA will cover include high energy particle physics, fusion engineering, operation regime development and, most importantly, plasma production and control schemes. JT-60SA experiments will also complement joint research with ITER by tackling some of the most challenging physical and technological issues that the future demonstration fusion power plants, such as DEMO, might face.

169. Plasma stability, material sciences and the impact of operational conditions related to DEMO were topics of the Sixth IAEA DEMO Programme Workshop, held in Moscow, Russian Federation, in October 2019. Close to 60 experts from 14 countries, the European Union's Fusion for Energy Organization and the ITER Organization participated in the event. During the Workshop[2], which takes place every two years, the main scientific and technical challenges of DEMO are discussed, and programmes, tasks and various possible courses of action are analysed. Although each participant may have individual research priorities, the objective of these workshops is to coordinate mutually beneficial efforts and facilitate international collaboration.

170. In 2019, the US Department of Energy launched a domestic programme for fusion that focuses on major technology developments, including a number of initiatives for funding and promoting public-private partnerships. This initiative aims to act as a pilot programme to leverage opportunities in critical fusion R&D areas and to accelerate progress towards the development of fusion energy.

171. Meanwhile, a significant number of private companies, as well as public–private partnerships, have been established in the last five years, mostly in Canada, the United Kingdom and the United States of America, but also in other European countries and China. In this context, the Fusion Industry Association has been created in the United States of America as an international network of companies working to electrify the world with fusion energy and with the goal of promoting fusion as a new source of energy.

172. The emergence of these new entities, partially supported by private capital, is likely to change the traditional fusion development scenario, where progress was based on largely government-funded projects. Therefore, international guidelines and standards in the field will be needed to assist in the design and facilitate the licensing process, safety and security procedures, waste management plans and

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[2] For more information, see https://nucleus.iaea.org/sites/fusionportal/Pages/DEMO_landing.aspx.

the overall feasibility studies for future fusion reactors, including cost-benefit analysis and socio-economic impact assessment scenarios.

C. Accelerators and Research Reactors

C.1. Accelerators and Associated Instrumentation

173. This section presents major developments in accelerator technology, its applications and associated instrumentation. The most common accelerator applications include the production of radioisotopes for medical diagnosis and treatment of cancer; intense sources of X-rays for sterilization of medical equipment and food products; charged particle beams for materials sciences analysis and irradiation; radiocarbon dating; accelerator-based neutron production with applications ranging from mineral and oil prospecting to nuclear data measurements or intense spallation neutron sources.

C.1.1. Dual-beam Facility Opens New Opportunities for Materials Research

174. A dual ion-beam facility (Figure C-1), which enables two ion beams from different accelerators to be combined simultaneously, has been inaugurated in Zagreb, strengthening Croatia's materials research and expanding the global reach of facilities with such cutting-edge capabilities.

175. Installed with IAEA support, the Ruđer Bošković Institute's He Ion Source and DiFU Dual-Beam Facility will help scientists test and develop new structural materials used in various energy technologies. Fission and fusion reactions generate not only highly energetic neutrons but can also produce gas (hydrogen and helium) that, after some time of exposure, can damage reactor structures and components. Ion beam technology can simulate these extreme conditions and help to develop new materials that are strong enough to sustain them.

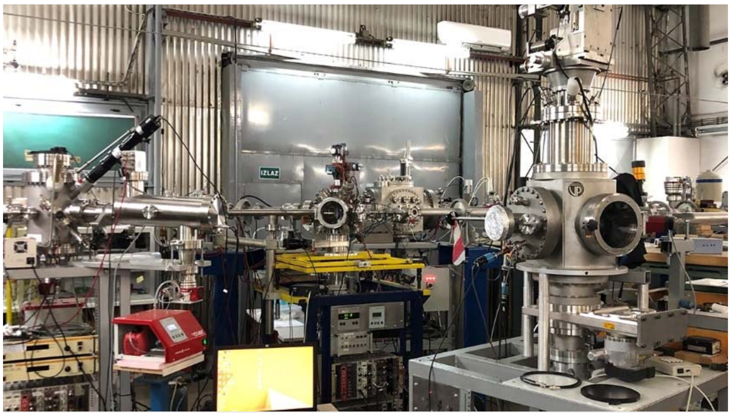

FIG. C-1. The He Ion Source and DiFU Dual-Beam Facility at Croatia's Ruđer Bošković Institute. (Source: IAEA)

176. In such a facility, two beams are directed at a steel sample — the material typically used for nuclear reactors owing to its robustness — to simulate how fission or fusion reaction products could interact with and modify this material. This nuclear interaction, in addition to possibly damaging the crystal structure of the material, creates transmutation gas products such as helium and hydrogen. This could lead to the formation of bubbles inside the steel, which can cause the material to swell. By knowing how and when these reactions occur, scientists can adapt the material to counteract these unwanted effects.

C.1.2. MACHINA — Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis

177. MACHINA is a next-generation compact particle accelerator, developed through international collaboration between the National Institute of Nuclear Physics (INFN) in Italy and the European Organization for Nuclear Research (CERN) in Switzerland, and has the potential to provide a breakthrough in the in-situ elemental analysis of cultural heritage objects. MACHINA addresses the demand from curators, art historians and restorers for in-situ, non-invasive ion beam analyses of works of art — a key factor for the study of immovable and priceless artworks, e.g. fragile frescoes and large or transport-sensitive paintings.

178. As shown in Figure C-2, MACHINA is a compact and transportable system based on the High Frequency Radio Frequency Quadrupole (HF-RFQ) technology developed by CERN. It has low weight (approximately 300 kg), is easy to transport and takes only two hours to dismount/reassemble the entire system. It is robust and extremely compact (2.5 m x 0.6 m footprint, with an adjustable height of about 1 m) and has an ultra-low power consumption (7–8 kW total power). The first prototype[3] will be used at the Opificio delle Pietre Dure in Florence, Italy, and is expected to be made available to other European laboratories and museums.

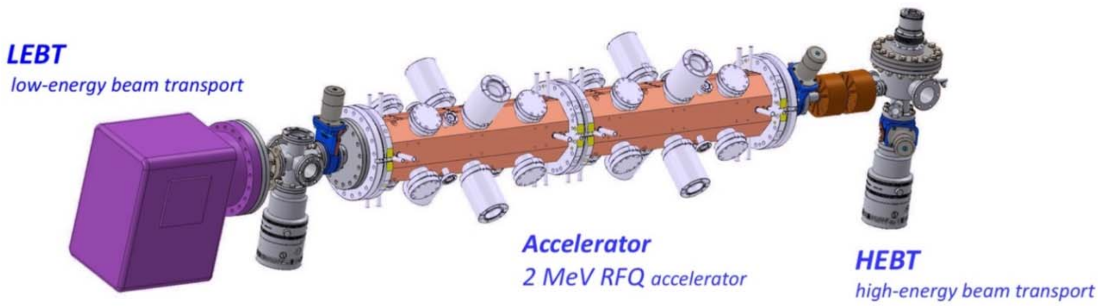

FIG. C-2. Schematic drawing of the main components of MACHINA. The ion beam can be extracted on the high-energy side of the accelerator to analyze the artifact. The very first applications are based on the PIXE technique, where X-rays are generated owing to particle-matter interactions. The emitted X-rays are then detected and, after data evaluation, the sample composition is determined. (Photo: MACHINA project)

C.1.3. Imaging of Whole Cells Using Focused Megaelectronvolt Ion Beams

179. The ability to see image structures inside whole cells at spatial resolutions below 100 nanometres is important for a wide range of applications in biology, including drug delivery, radiobiology and particle therapy (imaging radiosensitizers). Highly focused ion beams generated from megaelectronvolt (MeV) accelerators offer unique opportunities for these applications. By simultaneously detecting the energy of transmitted ions (scanning transmission ion microscopy (STIM)) and the visible light that they generate, researchers can record images for exploration of both structure and particle localization. This form of quantitative correlative microscopy can be a powerful tool for studying the structure and function of cells. Figure C-3 shows that nanoparticles have difficulty entering the cell nucleus, so direct DNA damage may be hindered during subsequent irradiation of the cell in radiobiology experiments.

[3] For more information, see http://home.infn.it/en/media-outreach/2015-03-26-11-50-59/2693-piccolo-preciso-e-potente-arriva-machina-l-acceleratore-per-i-beni-culturali-2.

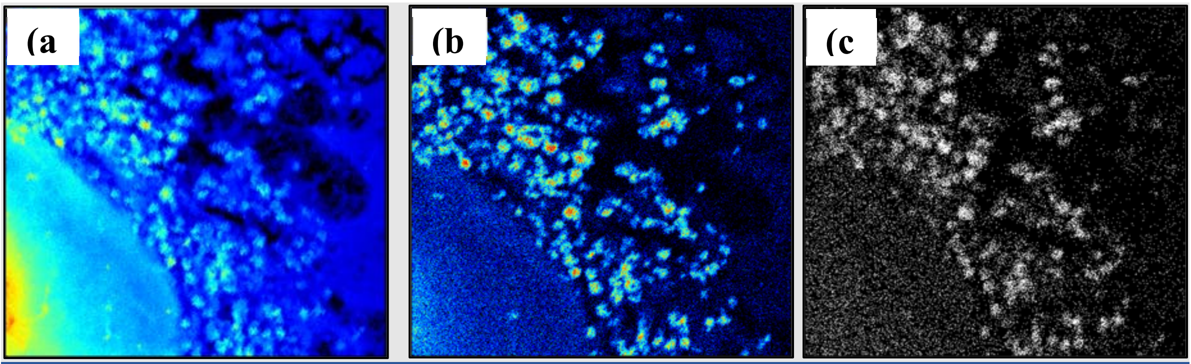

FIG. C-3. Image (13 µm scan size) of the uptake of rare earth up-conversion nanoparticles in a HeLa cell. The accumulation of 100 nm nanorods at the edge of the nucleus of the cell is explored by using three ion beam imaging modalities: (a) on-axis STIM showing density; (b) off-axis STIM showing enhanced scattering of nanoparticles; and (c) alpha particle induced fluorescence. A beam of 1.6 MeV alpha particles was used to image this cell with a spatial resolution of below 50 nm. (Images courtesy of Andrew Bettiol, Centre for Ion Beam Applications, Department of Physics, National University of Singapore.)

180. Indeed, nanoparticles can be used to target specific regions of the cell such as the mitochondria. In a radio-sensitization experiment (in the case of particle therapy), it may desirable to visualise the effect of radiation damage to mitochondrial DNA that has been enhanced by these nanoparticles. Cell mitochondria are approximately the size of a micron, so high resolution imaging is crucial. Mitochondria can be simultaneously targeted with fluorescent probes and nanoparticles, so a correlative approach to imaging is useful in localizing the mitochondria and the nanoparticles. A systematic study of the location of nanoparticles and the effect of varying irradiation doses can then be undertaken.

C.1.4. Laser Driven Accelerator Technologies Promise Diverse Applications

181. Recent advances in high-power laser technology[4] have led to the development of lasers producing extremely short light pulses in the femtosecond range with very high intensities exceeding 10^{21} Watt/cm^2. By guiding these pulses onto a solid foil, intense sources of photons, ions and neutrons can be generated (Figure C-4), which can subsequently be used for a wide spectrum of applications, such as non-destructive testing methods in aerospace; radiographic imaging of large objects; in-operando diagnostics of lithium-ion batteries; radiation processing to fabricate smart, functional materials; and active interrogation of sensitive nuclear materials, including nuclear waste characterization.

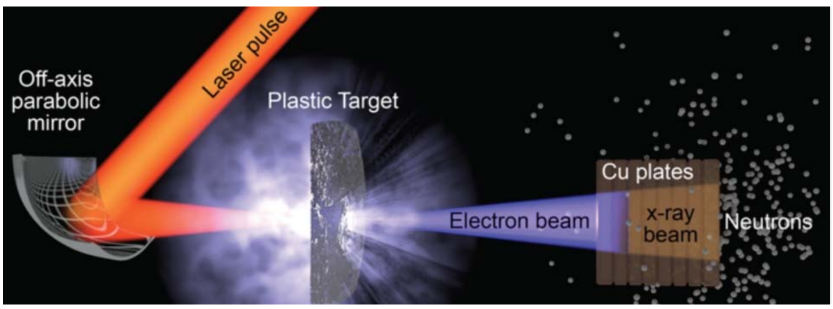

FIG. C-4. Schematic representation electrons and secondary neutrons being produced using laser based accelerating technologies. (Photo: Ishay Pomerantz, Tel Aviv University, Israel)

[4] Source: Side event at the 63rd regular session of the Agency's General Conference entitled "Laser-Driven Neutron Sources for Nuclear Applications", organized by Germany.

182. To date, laser-based techniques demonstrate potential to support accelerating electric fields at least four orders of magnitude larger than those of conventional accelerators and the goal of the international scientific community of producing miniaturized and portable particle accelerators appears to be feasible within the next decade.

C.2. Research Reactors

183. The most frequent applications for research reactors are shown in Figure C-5. Their power can range from zero (e.g. critical or subcritical assemblies) to approximately 200 MW(th), which are small relative to the 3000 MW(th) for a typical NPP. There is much greater design diversity for research reactors than for power reactors, and they also have different operating modes — steady or pulsed.

FIG. C-5: Common applications of research reactors around the world [a]

[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 237 research reactors considered (224 operational, 13 temporarily shut down, as of 31 December 2019).
[c] Other applications include calibration and testing of instrumentation, shielding experiments, creation of positron sources and nuclear waste incineration studies.

According to the Agency's Research Reactor Database, 818 research reactors have been built in 67 countries, of which 250 are in operation in 54 countries. The Russian Federation has the largest number of operating research reactors (59), followed by the United States of America (50), China (17) and Germany (7). Worldwide, 63 research reactors operate at a power level of 5 MW or higher and thus offer high neutron fluxes for industrial and medical products and services. In total, 9 research reactors are under construction in 6 countries, and 14 research reactors are planned in 11 countries.

184. Research reactors are 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. As many ageing research reactors retire, the remaining and new facilities must be used efficiently, be well managed and be operated sustainably and efficiently. The Agency encourages research reactor operators to develop or update strategic plans for the use of their facilities. In the past 3 years, 23 facilities submitted their strategic plans to the Agency for further advice. In 2019, the Agency developed the Integrated Research Reactor Utilization Review (IRRUR) to assist Member States in optimizing the utilization of their research reactors and conducted the first pilot IRRUR mission in Italy.

185. More than half 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 of reductions in funding for such facilities and limited succession planning, sound management systems, operation and maintenance and life management programmes will be vital so that they can fulfil their missions in a cost-effective manner. In this regard, Operation and Maintenance Assessment for Research Reactor (OMARR) peer review missions have been very useful and have been undertaken by Bangladesh, the Democratic Republic of Congo, Indonesia, Portugal, Thailand and Uzbekistan. Several of the 58 research reactors that are in permanent shutdown status in 23 Member States are expected to start preparing for decommissioning in the near future.

186. New research reactors are being constructed in Argentina, France, the Republic of Korea, the Russian Federation, Saudi Arabia and Ukraine (an ADS). Several Member States have formal plans to construct new ones, including Belarus, Belgium, Bolivia, the Netherlands, Nigeria, Tajikistan (completion of the Argus-FTI reactor), Thailand, the United States of America, Viet Nam and Zambia. Others, such as Azerbaijan, Bangladesh, Ethiopia, Ghana, Kenya, Malaysia, Mongolia, Myanmar, Niger, the Philippines, Senegal, South Africa, Sudan, Tunisia and the United Republic of Tanzania, are considering building new facilities. Integrated Nuclear Infrastructure Reviews for a new Research Reactor (INIR-RR) provide support and guidance to Member States embarking on a new research reactor project. INIR-RR missions have been conducted in Nigeria and Viet Nam and are in progress in Thailand and Zambia.

187. Member States that plan to build or preserve national nuclear capacity for their science and technology programmes, including nuclear power, continued to show interest in accessing research reactors. Thus, in 2019, the Agency consolidated and expanded its four instruments and tools: the Internet Reactor Laboratory (IRL), a distance training tool mainly for academic education (broadcasting sessions continued in 2019 for the Latin America and Caribbean regions, an IRL host reactor was commissioned in Morocco and significant progress was made in setting up IRL reactors in the Asia and the Pacific region and in Europe); the Research Reactor Regional Schools, for basic training; the Eastern Europe Research Reactor Initiative (EERRI) for advanced hands-on training, mainly for young professionals (in 2019, a Research Reactor School was organized in Japan and the 15th EERRI Training Course took place in Austria, Slovenia and the Czech Republic); and the IAEA-designated International Centre based on Research Reactor (ICERR) scheme for specific, advanced training for young and senior professionals.

188. To date, 99 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 2019, preparations began for the return of HEU fuel from the IVG.1M research reactor in Kazakhstan to the Russian Federation following the conversion of IVG.1M to LEU fuel. Preparations also began for the down-blending of HEU fuel of the IGR research reactor in Kazakhstan to the enrichment level below 20%

189. By the end of 2019, the programme for the return of US origin HEU fuel had completed the removal of approximately 1600 kg of fresh and spent HEU research reactor fuel, the Gap Remove Program completed the removal or confirmed disposition of approximately 2875 kg of HEU fuel and the Russian origin return programme had completed the removal of approximately 2300 kg.

190. International efforts to convert medical isotope producers from the use of HEU to LEU targets continued. Brief outages at some global molybdenum-99 target irradiation facilities and processors in 2019 resulted in some regional supply shortages. Efforts by supply chain management bodies and major international producers, as well as effective mitigation efforts by health practitioners, compensated for some of the production fluctuations. Approximately 75% of the molybdenum-99 sold in the world is now produced without the use of HEU fuel or targets. A new molybdenum-99 producer in the United States of America started commercial operation in 2018 using non-uranium based targets and began expansion of its production facilities in 2019.

D. Radioisotopes and Radiation Technologies

D.1. Facing the Burden of Plastic: Application of Nuclear Techniques

191. The rapidly growing production of plastic and the subsequent plastic waste causes enormous problems for the environment. The extensive use of easily available and relatively inexpensive synthetic polymers, including thermoplastics (commonly referred to as ‘plastics’) and rubber, have generated huge amounts of polymer wastes and created corresponding challenges in waste management in outdoor environments.

192. Polymers are widely used because of their low cost, easy fabrication, light weight and good mechanical properties. Increasing world population, combined with the advantages of these materials, has led to a dramatic increase in the environmental burden of plastic worldwide. Over the past 20 years, the production of synthetic polymers has increased by 240 %. If this trend continues, by 2050, about 12 billion tonnes of polymer waste will end up in landfill sites or in the environment.[5]

193. Many polymer wastes represent compositions of different materials that are difficult to separate, or are even inseparable, rendering their reuse problematic. Unlike natural polymers, synthetic polymers degrade slowly and gradually break up into small particles, known as microplastics, that contaminate the ecosystem. The latest statistical data on the amount of plastic waste ever produced show that, as of 2015, approximately 6300 million tonnes of polymer wastes have been generated (5800 Mt in primary generation and 500 Mt in secondary generation), around 9% of which have been recycled, 12% incinerated and 79% were discarded, accumulated in landfill sites or the natural environment.

194. Currently, mitigating this waste burden relies on multiple technologies whose application depends on local, regional and national drivers for both waste management and mitigation. The average rate of recycling worldwide is still low and varies according to country (Table D-1).

[5] Geyer, R., Jambeck, J.R., Law, K.L., Production, use, and fate of all plastics ever made, Science Advances 3(7):e1700782 (2017).

Table D-1. Global plastic recycling

Region/country	Recycling (%)	Energy recovery (%)	Managed: landfilled (%)	Mismanaged (unknown) (%)
Africa	12	1	26	62
Asia and Oceania	24	25	15	37
Europe (incl. Turkey)	27	31	33	9
Northern America	11	13	72	4
South and Central America (incl. Mexico)	15	11	30	44

Data source: Global Plastics Flow 2018 (Conversio Market & Strategy, February 2018,[https://www.conversio-gmbh.com/res/Global_Plastics_Flow_Feb10_2020.pdf)](https://www.conversio-gmbh.com/res/Global_Plastics_Flow_Feb10_2020.pdf)

195. To date, the recycling of polymer wastes is carried out by large facilities that rarely use radiation treatment. Radiation technologies (Figure D-1) fulfil the key principles of 'green' chemistry and provide manifold possibilities in the processing of materials via the controlled formation or cleavage of chemical bonds.

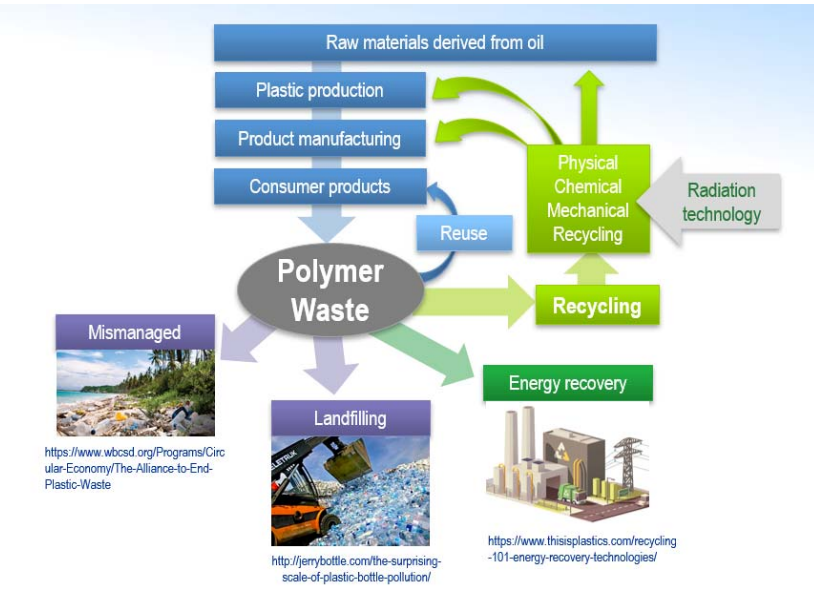

FIG D-1: Life cycle of plastic products and the generation and treatment of plastic waste. (Source: IAEA)

196. Member States are increasingly requesting the adaptation of radiation technologies to the global challenge of polymer waste recycling. Nuclear technologies have the potential to contribute in establishing a plastic circular economy and can complement conventional approaches to reducing plastic waste volumes. These radiation technologies are scalable, meaning they can be used for irradiating even large amounts of polymer wastes. This irradiation process can be used for two things: to modify the

plastic structure and properties or to break down the plastic to create feedstocks. In both cases, the modified or functionalised new material or the feedstock is used to generate commercially viable recycled-plastic consumer products, thus creating profitable benefits while reducing waste volumes.

197. Using radiation technologies has a distinct additional advantage in that radiation is a ‘green’ technology, bypassing solvents used in chemical polymer recycling, which would otherwise contribute to environmental pollution and carbon emissions. Recycling into new products using radiation technologies is particularly attractive when primary recycling of plastic waste is no longer possible, as many thermoplastics can only be recycled once or twice with conventional technology. As such, plastic waste recycling using radiation technology is an innovative contribution that can complement conventional plastic waste recycling approaches.

198. Nuclear techniques also offer reliable and accurate monitoring and assessment of impacts of marine microplastics in the environment using isotopic tracers. Isotopic tracers have an unparalleled degree of precision and sensitivity necessary for accurate determination of the occurrence, monitoring movements and assessment of plastic waste in the environment. This information can be used to guide policy decisions.

199. However, well-established radiation technology approaches for synthesis of new materials and disinfection of toxic liquids and gases cannot be directly transferred to polymer wastes. Therefore, new research and development is needed. Whenever possible, recycling and reuse of polymers is desirable and the efficiency, economy and sustainability of the recycling process is crucial.

> An emerging application that turns plastic waste into a material for sustainable and scalable applications is the use of such waste to improve the mechanical performance and durability of cement paste and concrete. The global production of cement is the third largest source of carbon emissions, and, therefore, the use of recycled plastic in concrete could also have an additional positive environmental impact.[6]

200. Future radiation facilities for plastics recycling should use cost-effective, integrated electron beam equipment available from small and medium-sized enterprises. It would be preferable for radiation modification of polymers to be carried out in an air atmosphere, without excessive pressure, using electron beam processing with optimized parameters. Standard regulation guidelines for material traceability should be considered from the outset of developing novel material systems based on recycled polymer waste.

[6] Schaefer, C.E., et al., Irradiated recycled plastic as a concrete additive for improved chemo-mechanical properties and lower carbon footprint, Waste Management 71 (2018) 426-439.

D.2. Breakthrough in Accelerator Technologies Brings Boron Neutron Capture Therapy to Hospitals

D.2.1. Progress in Compact Accelerator-based Neutron Sources

What is Boron Neutron Capture Therapy?

BNCT is a unique therapy based on the idea of selectively delivering boron compounds into tumour tissues, which are subsequently irradiated with neutrons. These neutrons are captured by boron, which is followed by the emission of alpha particles and the recoil of the lithium nucleus, both with very-high energy transfer within extremely short stopping distances comparable to the size of a single cell. Both the intracellular high biological effectiveness and the precisely localized tumour cell damage at the cellular level are the major advantages of BNCT in clinical therapy. With the recent advances in accelerator technologies, boron neutron capture therapy (BNCT) is one step closer to becoming a possible option for clinical cancer treatment.

201. BNCT has thus far been performed mainly at research reactors capable of offering the required intensity and quality of neutron beams for the irradiation of patients. In the last two decades, more than 1000 patients worldwide have been treated at such facilities, and significant progress has been made in optimizing boron compounds, including their usage and the control of their accumulation in the tumour cells. However, many of these reactors have been shut down or have discontinued their BNCT-related activities, in particular owing to the difficulty of combining a reactor environment with clinical requirements. Presently, only four reactors continue to offer BNCT as a possible cancer treatment. Nevertheless, there has been a significant increase in number of BNCT facilities and projects aiming to establish and operate compact neutron sources, based on particle accelerators, which are all located in university hospitals or cancer therapy centres. Some of these facilities have already started clinical trials, and more facilities are under consideration worldwide.

202. The different technology components of accelerator-based BNCT are illustrated in Figure D-2, which shows protons being accelerated to energies ranging from a few megaelectronvolts (MeV) to 30MeV, at average beam currents from a few to tens of milliamperes (mA) and colliding with light element targets, such as lithium (Li) or beryllium (Be). As a result, fast neutrons are produced, which, in turn, are collimated, moderated and guided to the patient irradiation area as represented schematically. Some key facility elements are also presented in Figure D-3.

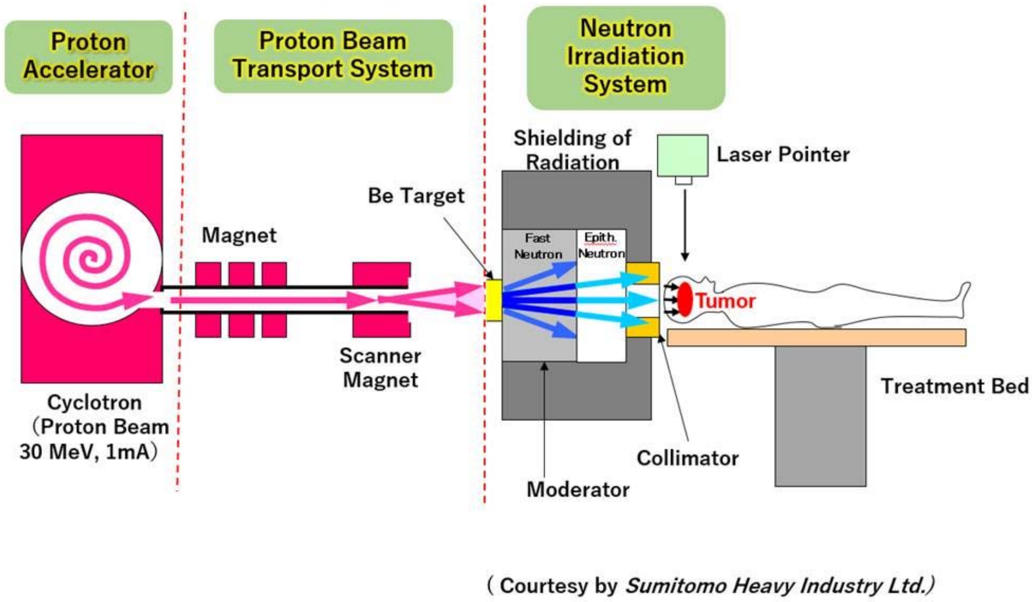

FIG. D-2. Schematic representation of accelerator-based BNCT. (Source: Sumitomo Heavy Industries, Japan).

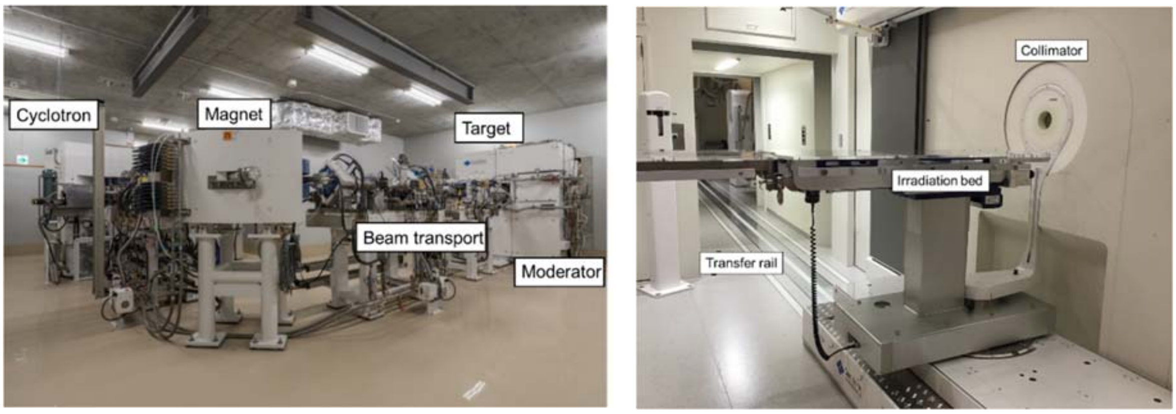

FIG. D-3. Accelerator and target components (left) together with patient irradiation position (right) at an accelerator-based BNCT centre. (Photos: Kansai BNCT Medical Center, Japan).

203. The Agency is currently reviewing and updating the IAEA Technical Document (TECDOC) entitled Current Status of Neutron Capture Therapy (IAEA TECDOC No. 1223), published in 2001, in order to reflect all results obtained from reactor-based BNCT facilities during the last two decades and to include new trends and progress made in accelerator-based in-hospital BNCT centres. Table D-2 summarizes different accelerator-based BNCT facilities with their technical parameters and status of completion.

Table. D-2. List of accelerator-based BNCT facilities with status of completion. (Source: IAEA).

Country	Facility	Accelerator	Projectile (incident energy) + target	Designed maximum (present) current (mA)	Present status
Japan	Kyoto University	Cyclotron	p(30.0MeV)+Be	1 (1)	Clinical trials
	Southern Tohoku BNCT Research Center				
	Kansai BNCT Medical Center				
	University of Tsukuba	Linear	p(8MeV)+Be	5 (1.8)	Commissioning
	National Cancer Center Hospital	Linear	p(2.5MeV)+Li	20 (12)	Clinical trials
	Edogawa Hospital BNCT Center				Construction
	Nagoya University	Electrostatic	p(2.8MeV)+Li	15 (1)	Commissioning
Finland	Helsinki University Hospital	Electrostatic	p(2.6MeV)+Li	30 (20)	Clinical trials*
Argentina	Bariloche Atomic Centre	Electrostatic	d(1.4MeV)+Be	30 (1)	Construction
Russian Federation	Budker Institute of Nuclear Physics	Electrostatic	p(2.0MeV)+Li	10 (2)	Developing
Israel	Soreq Applied Research Accelerator Facility	Linear	p(4.0MeV)+Li	20 (2)	Developing
China	Xiamen Humanity Hospital	Electrostatic	p(2.5MeV)+Li	10 (-)	Developing
Italy	National Institute for Nuclear Physics	Linear	p(4.0MeV)+Be	30 (-)	Developing
Republic of Korea	A-BNCT	Linear	p(10.0MeV)+Be	8 (-)	Developing

* Facility is operational and clinical trials are already planned.

D.2.2. Theranostic Radiopharmaceuticals and BNCT

204. Theranostic radiopharmaceuticals can be used as a combination of therapy and diagnosis that provides a transition from conventional medicine to a personalized, precision medicine approach. The effectiveness of BNCT depends largely on boron concentration and its distribution in targeted tumour cells. In most cases, boronophenylalanine (BPA) is used as a boron-10 (^{10}B) carrier in BNCT. BPA labelled with fluorine-18 (^{18}F-BPA) has been developed and successfully applied for monitoring the pharmacokinetics of BPA with positron emission tomography (PET). As a result, ^{18}F-BPA PET has made it possible not only to obtain information about the tumour but also to evaluate boron accumulation in both tumour and normal tissues and to indicate the tumour response to BNCT. Currently, ^{18}F-BPA PET-based BNCT is applied for various cancers, such as malignant gliomas, head and neck cancers, melanoma, mesothelioma, liver cancer and lung tumours (Figure D-5).

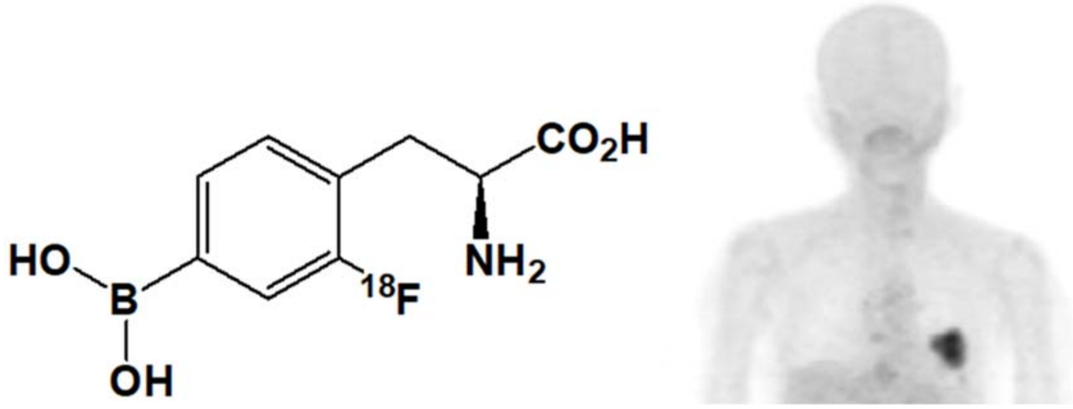

FIG. D-5. Left: Molecular structure of BPA labelled with ^{18}F (^{18}F-BPA). Right: PET image of boron compound accumulation in metastatic malignant melanoma of the lung. (Source: Osaka University, Japan).

205. The efficiency of BNCT could be further improved if boron concentration could be increased in target cells. Since BPA contains only one ^{10}B atom per molecule, there is a need for the development of cell targeting agents containing a higher number of ^{10}B atoms in their structure. Many research studies are in progress for introduction of such molecules worldwide; however, considering the long process of drug development, it will take some time for new molecules to be tested and applied in BNCT.

D.3. Medical Isotope Browser: A Tool for Novel Radioisotope Production Routes in the Fight Against Cancer and Other Diseases

206. The Agency has developed a new web-based tool that makes it possible to directly predict the production yield of a medical isotope on the basis of user input. The Medical Isotope Browser can be used by medical scientists and the radiopharmaceutical industry to discover radioisotope production routes not yet explored. This will contribute significantly to the fight against cancer and other diseases. The production of medical isotopes for therapy or diagnosis depends on very complex nuclear reaction processes, which are only available to nuclear physicists via measurements and nuclear reaction theories. The Medical Isotope Browser makes this fundamental information accessible to many non-specialist users through a graphical user interface.

207. The Medical Isotope Browser was officially released during the International Symposium on Trends in Radiopharmaceuticals, held by the Agency in Vienna in October–November 2019. The first version is restricted to isotopes produced by charged-particle accelerators. Users can specify the characteristics of the accelerator, such as the projectile (proton, deuteron, tritium, helium-3 or alpha particle), current in microamperes and the incident and exit energy, as well as the target material and the

desired produced radioisotope. The required isotopic yield as a function of irradiation and cooling time as well as a complete description of all the produced impurities can be obtained almost instantly. The next version will also include medical isotope production using research reactors and electron beams (Figure D-6).

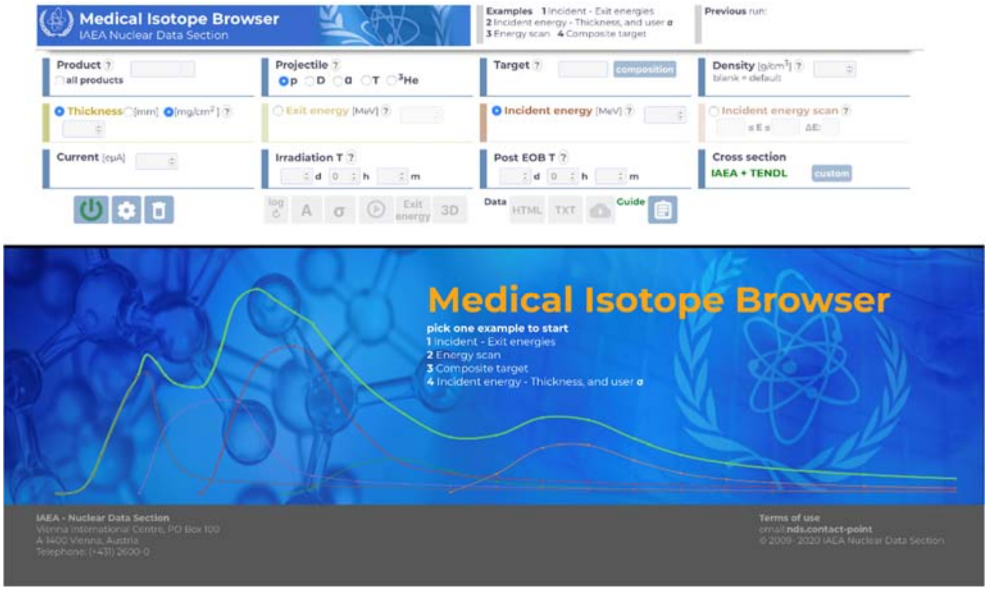

FIG. D-6. Homepage of the Medical Isotope Browser available at http://nds.iaea.org/mib

E. Human Health

E.1. New Dual Isotope Tracer Method for Protein Quality Assessment in Humans

E.1.1. Protein and its Implications for Child Growth and Development

208. The supply of protein in the first two years of life not only determines growth, but also influences the risk of later obesity and non-communicable diseases and can have an impact on the rate of recovery from acute malnutrition. Proteins are composed of both dispensable and indispensable amino acids. The former can be synthesized in the body while indispensable amino acids (IAAs) must be supplied through diet. Children at high risk of growth retardation often consume foods deficient in most IAAs, including tryptophan, methionine, threonine, phenylalanine and lysine. However, the available data on IAA requirements and digestibility for early child growth are insufficient.

E.1.2. Protein Quality

Did you know?

Protein digestibility varies according to the source of the protein; proteins of animal origin tend to be more digestible compared with proteins from plant-based diets.

209. Protein quality is defined as the measure of usefulness of a given protein to provide, when consumed, an adequate quantity of bioavailable IAAs to sustain body maintenance, growth, physiological needs, physical activity and ability to fight infection. The IAA composition of the protein, its digestibility and the subsequent amino acid absorption are important. These characteristics are combined into a protein quality score for a given food. For example, lysine and threonine occur in suboptimal amounts in most cereals, while methionine is found in inadequate amounts in legumes.

E.1.3. The Dual Isotope Tracer Method for Protein Quality Assessment in Humans

210. The currently available methods for measuring amino acid digestibility in the upper intestine are invasive, as they require access to the effluent leaving the small intestine, which is accomplished by intestinal intubation in humans. However, this can be performed in a relatively non-invasive manner by means of a dual isotope tracer technique using deuterium (^{2}H) and carbon-13 (^{13}C), in which an intrinsically isotope-labelled test protein is simultaneously fed with a different isotope-labelled ‘standard’ protein. The ‘standard’ protein is either a free amino acid mix (that requires no digestion) or a whole protein (isotope-labelled spirulina, for example) whose digestibility is pre-determined. The postprandial ratio of differently labelled IAAs in the blood then allows for the evaluation of the true IAA digestibility of the test protein. The technique was developed in response to a call from the Food and Agriculture Organization of the United Nations (FAO) in the context of an IAEA-supported CRP, entitled “Bioavailability of Proteins from Plant Based Diets”. As part of the CRP, protein quality was evaluated, based on the Digestible Indispensable Amino Acid Score that is recommended by FAO, in a wide variety of locally grown legumes in Brazil, India, Jamaica, Mexico, Morocco, Pakistan and Thailand, with technical support by experts from France and the United Kingdom. The method involves two phases, as described below.

E.1.4. Intrinsic Labelling of Legumes with Deuterium Oxide During Growth in the Field

211. Intrinsically labelled legumes are produced by applying a bolus of deuterium oxide (D_2O) as part of the watering routine of the legume plant. The plants are left to grow to maturity and the dry seeds are subsequently harvested (Figure E-1).

FIG. E-1: Intrinsic labelling of legumes using D_2O *during growth.*
(Photo: Ms Wantanee Kriengsinyos, Mahidol University, Thailand).

E.1.5. Human Study with Test Meals Prepared from Intrinsically Labelled Legumes

212. The dual isotope method is conducted in either an eight-hour (in adults) or six-hour (in children) feeding protocol. In adult protocols, five blood samples are collected (at baseline and then hourly at five, six, seven and eight hours after the test meal is consumed), while, in protocols for very young children, only three samples are collected, one at baseline and in the fifth to sixth hour. For example, the legume or food under test is intrinsically labelled using D_2O, while a small quantity of a ^{13}C-labelled 'standard' protein is included in order to compare IAA appearance from the test legume with that of the standard protein given simultaneously. A commercially available highly ^{13}C-enriched single cell protein (^{13}C-spirulina) can be used as a standard protein. The appearance of labelled amino acids in the blood relative to the test meal is used to calculate the digestibility of the legume protein (Figure E-2). Additionally, by adding a labelled amino acid (^{13}C-phenylalanine) to the test meal, amino acid absorption can be estimated from the appearance of this labelled amino acid in the blood.

FIG. E-2: Test meal and study participant consuming it.
(Photos: Wantanee Kriengsinyos, Mahidol University, Thailand).

E.1.6. Relevance of the Method

213. The method has already been applied in a cohort of infants and young children below two years of age in India to estimate the true IAA digestibility of four commonly consumed foods. Results showed that the digestibility of key IAAs, such as methionine and threonine, was very low. The study also showed a positive relationship between the amino acid digestibility score of the foods and child height. The emerging information on amino acid digestibility will greatly contribute to informing the FAO protein quality recommendations for humans at all ages, in line with Sustainable Development Goal 2 — achieving zero hunger worldwide. With the emerging crisis of climate change and water scarcity, both the protein content and yield of cereal protein sources are likely to decrease, while legume protein content may be less impacted. There is an opportunity to determine the protein content and digestibility of drought-resistant plant varieties and to project the future supply of high-quality protein using accurate techniques, such as the dual tracer method.

E.2. Biodosimetry as a Useful Diagnostic/Predictive Tool for Radiation Emergencies and Medicine

Biodosimetry helps to determine the dose of radiation received by an individual or a patient. This method uses biological markers such as chromosomal abnormalities, which can be seen using a microscope.

214. Biodosimetry uses biological samples, such as blood, usually taken from individuals who have been exposed to radiation, to assess the exposure they received, for example, through inhalation or ingestion. Electron paramagnetic resonance of tooth enamel or bone is also used for retrospective

dosimetry, and this method is sometimes referred to as biodosimetry. In the event of a radiation or nuclear emergency, biodosimetry is essential for timely determination of the radiation dose received by the exposed individuals (e.g. exposed workers or the general public). Retrospective biodosimetry may even help reveal radiation exposure from years before, such as in the Chornobyl accident or even the atomic bombings of Hiroshima and Nagasaki. Biodosimetry could also be used for clinical applications, such as helping radiation oncologists to improve medical outcomes.

E.2.1. Biodosimetry Relates Biomarkers to Doses

215. Biodosimetry is one of the most developed branches of radiobiology; its technical aspects are well refined and have reached international standardization.[7] There are four ISO standards for biodosimetry, which provide international guidance for implementation of biodosimetry services: ISO 19238:2014, ISO 21243:2008, ISO 17099:2014 and ISO 20046:2019.

216. In short, calibration curves are used to relate biomarkers to the dose received by a patient (Figure E-3.). Determining the dose is important for choosing the right medical strategy to treat an individual exposed to radiation in accidents. Calibration curves are the result of mathematical modelling based on empirical data; errors are not shown.

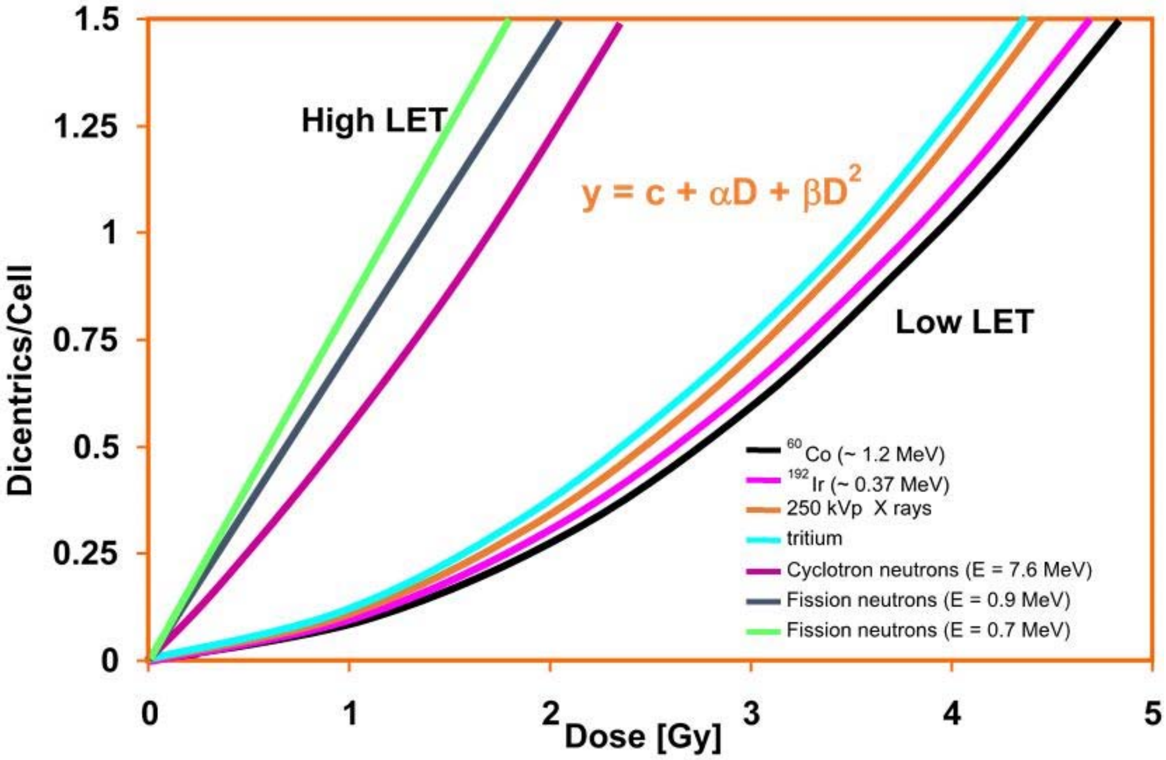

FIG. E-3 Linear and linear quadratic dicentric dose response curves for high and low linear energy transfer radiations. (Source: Cytogenetic Dosimetry: Applications in Preparedness for and Response to Radiation Emergencies – Training Materials, Emergency Preparedness and Response, EPR-Biodosimetry/T 2012, IAEA, 2013.)

[7] IAEA, Cytogenetic Dosimetry: Applications in Preparedness for and Response to Radiation Emergencies, EPR-Biodosimetry 2011 (2011) p. 142.

E.2.2. Standard Biodosimetry Methods

217. There are four standardized methods of cytogenetic biodosimetry in use: (i) conventional unstable chromosome aberrations ('dicentric') analysis; (ii) measurement of stable chromosome aberrations with the fluorescent in situ hybridization (FISH) method ('translocation analysis'); (iii) premature chromosome condensation (PCC) analysis; and (iv) the cytokinesis-block micronucleus (CBMN) assay.

E.2.3. Highlights of New Biodosimetry Methods Developed Since 2000

218. Several new methods have recently been introduced to biodosimetry practice that are revolutionizing the field.[8] Radiation-induced dicentric chromosomes in human lymphocytes can be detected using the peptide nucleic acid–FISH (PNA–FISH) method (Figure E-4). This constitutes an improved method for determining unstable chromosome aberrations, which allows dicentric aberrations to be scored more efficiently. Use of telomere and centromere probes in hybridization can enhance the resolution of dicentric chromosome detection in the analysis.

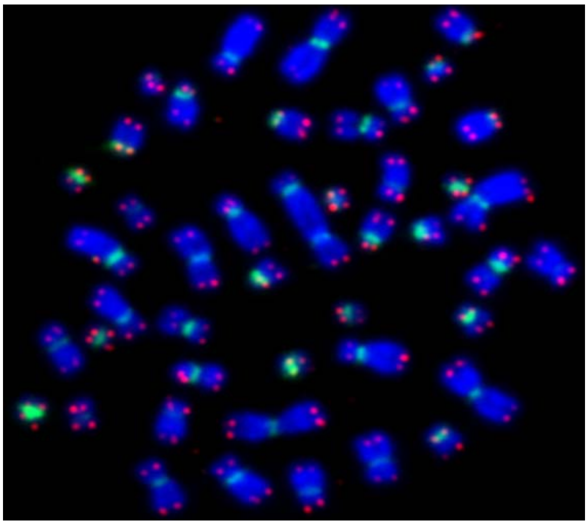

FIG. E-4. PNA–FISH cyanine 3 (telomere) and fluorescein isothiocyanate (centromere) PNA probes, depicted by the red and green signals, counterstained with 4',6-diamidino-2-phenylindole shown in blue. (Photo: Prof. Hande, National University of Singapore.)

219. The multicolour fluorescence in situ hybridization (mFISH) technique is another method, which allows detection of interchromosomal aberrations in the form of a chromosomal translocation induced by ionizing radiation in human lymphocytes (Figure E-5).

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[8] Zeegers, D., et al., Biomarkers of Ionizing Radiation Exposure: A Multiparametric Approach, Genome Integrity 8(1) (2017).

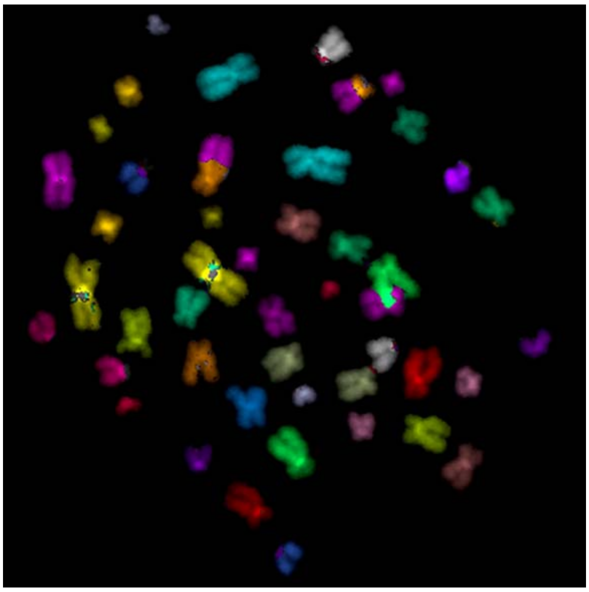

FIG. E-5. In the mFISH technique, each chromosome (1 to 22, X and Y) is painted in a different colour using combinatorial labelling producing a 24-colour hybridization so that any interchromosomal translocations are observed as colour junctions on individual chromosomes. (Photo: Prof. Hande, National University of Singapore.)

220. Finally, the multicolour chromosome banding (mBAND) technique is arguably the most advanced biodosimetry method, as it allows intra-chromosomal aberrations to be detected. This kind of biomarker is considered to be a unique signature of high linear energy transfer radiation (Figure E-6).[9]

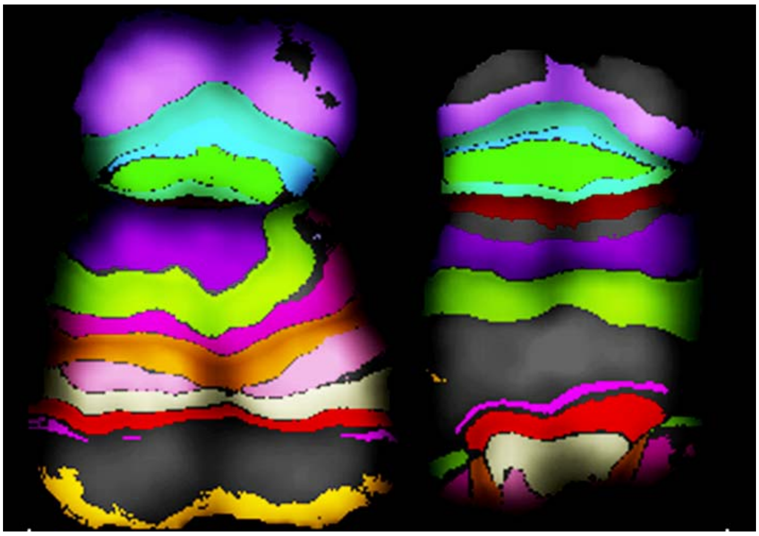

FIG. E-6. mBAND FISH intrachromosomal aberrations in chromosome 5 detected by use of region-specific chromosome paints. (Photo: Prof. Hande, National University of Singapore.)

[9] Vinnikov, V. and Belyakov, O., Clinical Applications of Biomarkers of Radiation Exposure: Limitations and Possible Solutions through Coordinated Research. Radiat Prot Dosimetry, 2019.

E.2.4. Future Directions

221. New biodosimetry methods help to identify radiation exposure in humans, quantify it and elaborate on the possible source and character of the exposure. Biodosimetry methods have recently been introduced to radiation oncology and nuclear medicine, as well as diagnostic and interventional radiology.[10] The Agency has launched a new CRP that addresses the issue of facilitating dialogue between biodosimetry specialists and radiation oncologists.[11] It is expected that the remarkable improvement in biodosimetry methods will allow for a more comprehensive assessment of the consequences of planned or accidental medical radiation exposures.

F. Food and Agriculture

F.1. Enhanced Applications of the Sterile Insect Technique in Prevention and Eradication of Invasive Insect Pests

F.1.1. Background

222. Invasive species can interfere with ecosystem services or disrupt whole ecosystems and cause the decline of many of the native species that are now listed as endangered or threatened.[12] The impacts of invasive species are second only to habitat destruction as a cause of global biodiversity loss.[13] The significant costs of invasive-pest control and forgone output is a cross-boundary issue requiring effective regional and international coordination.

223. The rapidly increasing rates of international transport and trade, population migration, moving of livestock and agricultural commodities between geographical regions have significantly increased the probabilities of introducing invasive pest species into new regions. The rate of non-native species introductions has grown in the past 200 years from an average of 7.7 per year between the years 1500 and 1800 to a record 585 in 1996.[14] Over time, arthropods and other invertebrates have become increasingly effective invaders, with an exponential increase in introductions in the past 45 years. It has been estimated that the damage to the world economy inflicted by invasive species is around $1.4 trillion, which in 2002 represented about 5% of the total world economy.

F. 1.1.1. Relationship between Invasive Insect Pests and Climate Change

224. Climate change resulting from anthropogenic greenhouse gas emissions is not only inducing changes in the distribution of many species but also facilitating increased survival of invasive pests in previously inhospitable regions.[15] Whereas the increase in movement and exchange of goods is accelerating the redistribution of many insect pests, climate and related land use changes will likely

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[10] Vinnikov, V. and Belyakov, O., Radiation Exposure Biomarkers in the Practice of Medical Radiology: Cooperative Research and the Role of the International Atomic Energy Agency (IAEA) Biodosimetry/Radiobiology Laboratory. Health Physics, 2020.
[11] *Ibid.*

[12] Charles, H., Dukes, J., Impacts of invasive species on ecosystem services, Ecological Studies 193 (2007) 217–237.

[13] Pimentel, D., (Ed.) Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal and Microbe Species, 2nd edn. (2011) CRC Press, Boca Raton, 369. This publication is referred to several times in Section F.

[14] Hulme, P. E., Trade, transport and trouble: managing invasive species pathways in an era of globalization, Journal of Applied Ecology 46 (2009) 10–18.

[15] Ziska, L. H., Dukes, J. S., (Eds.) Invasive species and global climate change, (2014) CABI, Wallingford, 368.

create new ecological niches, allowing the establishment of new pests in new territories and significant species range shifts (Figure F-1).

FIG. F-1. Example of an invasive insect pest (Cactus moth, Cactoblastis cactorum (Berg)). (Photo: Ignacio Baez, Center for Plant Health Science and Technology, United States Department of Agriculture)

225. Climate change projections to 2050 predict a net average increase of 18% in the occurrence of arthropod invaders. This expansion applies not only to plant pests, but also to vector-borne diseases, affecting not only the spatial-temporal distributions and population dynamics of the vectors, but also speeding up their life cycles, including those of parasites, their modes of transmission and opportunities for development in new hosts. Higher temperatures can increase the rate of development of pests and pathogens, shortening their generation times and thus increasing the number of generations per year, which, in turn, can lead to higher pathogen/parasite population sizes and the probability of mutations to more virulent strains. To mitigate or address these climate- and globalization-induced new pest problems, new legislation and policies are required.[16] Among these is the need to support the development of innovative control approaches, such as the sterile insect technique (SIT), to mitigate and manage these biological incursions, and to contain the geographical expansion of non-indigenous pest populations.

F.1.1.2 The SIT as a Tool for Preventing and Eradicating Invasive Insect Pests

226. Campaigns to eradicate invasive insect pests often lack the tools to surgically remove all individuals of a target population and must rely on indiscriminate and large-scale application of insecticide sprays, as well as the drastic removal of infested animals and plants, or even the massive destruction of whole herds, crops and orchards.

[16] Perrings, C., Dehnen-Schmutz, K., Touza, J., Williamson, M., How to manage biological invasions under globalization, Trends in Ecology and Evolution 20(5) (2005) 212–215.

Deployment of SIT

SIT, deployed as an important component of an area-wide integrated pest management (AW-IPM) approach, can prevent the establishment of, and contain and eradicate, an invasive population without raising public opposition or leaving an ecological footprint. As it is species-specific, and therefore does not affect other beneficial or non-target organisms, it is an ideal tool to help eradicate invasive insect pest populations. Its integration, especially in the later phases of eradication campaigns, is particularly effective in view of its inverse density-dependence: the lower the target population, the sooner it will reach the objective of eradication. It also integrates well with other biologically based suppression methods. It can be applied by air, and consequently is effective over irregular topography and areas with limited access.

F.1.2. Improved SIT Technologies and Strategies

227. In the past decades, improved technologies and protocols for mass production, sterilization and release of sterile insects have greatly enhanced the cost-effectiveness of AW-IPM with a SIT component. This has opened the door to expanding the use of the technology to other key insect pests, including high-profile invasive pests that affect plants, animals and human health. This includes the use of SIT to eradicate outbreaks from pest incursions and recent incipient establishment. If Member States face the introduction of an invasive species, data on the recommended doses for sterilization of insects is compiled and available for more than 360 insect species at the International Database on Insect Disinfestation and Sterilization (IDIDAS).

228. An example of a preventive SIT approach is the preventive release programmes against the Mediterranean fruit fly in California and Florida.[17] These US states have been increasingly subject to incursions of the Mediterranean fruit fly, leading to repeated detections and outbreaks in urban areas, especially those with international airports. The incursions have been linked to fruit smuggling, as well as the rapidly growing volume of shipments and air traffic. This triggered extensive and costly eradication programmes, initially largely based on aerial malathion bait sprays over urban areas that caused much public outrage. In response, in California, a Mediterranean fruit fly preventive release programme (PRP) was initiated in 1994 that now covers 4582 km2 in the Los Angeles Basin and Orange County. Compared with pre-PRP years, outbreaks in California have been reduced by more than 98%. In PRP areas in Florida, no Mediterranean fruit fly outbreaks have occurred.[18] As a result, despite continuous incursions of this invasive pest, the continental United States of America is still internationally recognized as Mediterranean fruit fly-free.

229. An example of SIT use to eradicate outbreaks from pest incursions and recent incipient establishment is the eradication of the Mediterranean fruit fly from the Dominican Republic. The Mediterranean fruit fly presence was reported in March 2015 in the Dominican Republic. An import ban was immediately put in place by the Dominican Republic’s major trading partners, resulting in an estimated loss of about $40 million in fruit and vegetable exports and putting thousands of jobs at risk. As an emergency response, the Government of the Dominican Republic established the Moscamed Programme-DR.

[17] Dowell, R. V., Siddiqui, I. A., Meyer, F., Spaugy, E. L., Mediterranean fruit fly preventative release programme in southern California, 369–375. In Tan, K. H., (Ed.) Proceedings: Area-Wide Control of Fruit Flies and Other Insect Pests. International Conference on Area-Wide Control of Insect Pests, and the 5th International Symposium on Fruit Flies of Economic Importance, 28 May–5 June 1998, (2000) Penerbit Universiti Sains Malaysia, Malaysia.

[18] United States Department of Agriculture, 2014 Review of Sterile Insect Release Facilities: Sarasota, Florida and Los Alamitos, California. Mediterranean Fruit Fly Preventive Release Program, (2014) 30.

230. The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, in close cooperation with the United States Department of Agriculture and the Guatemala–Mexico–USA Moscamed Programme, provided technical assistance to the Dominican Republic to suppress this major invasive pest and to implement the SIT as the main eradication tool. Other organizations that participated in this major effort to assist the Dominican Republic were the International Regional Organization for Plant and Animal Health and the Inter-American Institute for Cooperation on Agriculture. From October 2015 until May 2017, over 4 billion sterile flies were shipped from the El Pino facility in Guatemala and released in the affected areas (Figure F-2). The eradication of the Mediterranean fruit fly was officially declared in July 2017.[19] Had this devastating invasive pest been allowed to establish itself, the whole Caribbean region and all its trading partners would have been at severe risk of devastating outbreaks and huge losses in export revenue.

FIG. F-2. Preparation for aerial release of sterile insects. (Photo: Moscamed Programme Guatemala.)

F.1.3. Prevention and Preparedness Against Invasive Insect Pests

231. For many regions or countries currently free of certain pest species, it is a matter of when, rather than if, these pests will invade (Figure F-3). Trends in global travel and trade make it increasingly likely that any species can reach anywhere in the world.

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[19] Zavala-López, J. L., Marte-Diaz, G., Martínez-Pujols, F., Successful area-wide Mediterranean fruit fly eradication in the Dominican Republic. *In* J. Hendrichs, R. Pereira and M.J.B. Vreysen (Eds.), Area-wide integrated pest management: development and field application (to be published).

FIG. F-3. Luggage phytosanitary inspection at point of entry by dogs detecting immature stages of invasive species. *(Photo: FUNBAPA, Argentina.)*

232. Cost–benefit analyses generally show that preparations for incursions that enable a rapid and effective response are much cheaper than having to run large and costly eradication campaigns with uncertain success, or letting a major pest become permanently established that then requires long-term control. There is great potential for applying the SIT against major invasive insect pests; however, the SIT package is often only partially or not available when new invasive-pest outbreaks occur. Therefore, it is important to develop the SIT package for the worst potential non-indigenous pests that are amenable to SIT application.[20]

233. The optimization of the technology used for area-wide SIT applications, as well as its diversification to combat other high-profile insect pests, will further expand the use of the technique and will constitute a strategic tool for combatting the increasing introduction of invasive pests owing to factors such as increased travel and trade, and climate change.

F.2. The Use of Nuclear Techniques to Support Food Traceability Systems

F.2.1. Background

234. Numerous foods are sold at premium prices because of 'added-value' labelling claims related to specific geographical origins, production methods and unique characteristics. Origin-linked products can be part of a virtuous circle of sustainable quality based on the preservation of local resources and other factors described in the FAO publication "Linking people, places and products"[21].

235. The most promising analytical methods for verification of geographic indication include stable isotope and trace element (SITE) analysis; magnetic resonance spectroscopy, including nuclear magnetic resonance (NMR) and electron paramagnetic resonance or electron spin resonance spectroscopy; and mass spectrometric profiling. Furthermore, there is a recommendation from the European Union that newly registered geographic indications should contain a reference to a suitable analytical procedure to verify the provenance and/or essential qualities of the product.

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[20] Invasive Species Specialist Group, Global Invasive Species Database, Global Invasive Species Programme (GISP) (2018). http://www.issg.org/database/species/search.asp?st=100ss&fr=1&str=&lang=EN

[21] FAO, Strengthening sustainable food systems through geographical indications: An analysis of economic impacts (2018).

What is Geographic Indication?
Geographic indication' defines the origin and/or production method of a food where a given quality, reputation or other characteristic of the food is essentially attributable to its geographic origin or terroir. The benefits of geographic indication include quality assurance (reputation), fair competition, protection of the name on the markets (domestic or international), price premium, linking valuable products to rural areas, reconnecting consumers and producers, and protecting traditions. An overview of registered geographic indication products can be found in the European Union's Database of Origin and Registration (DOOR) of agricultural products and foodstuffs, comprising several thousand food products from around the world.

F.2.2. Nuclear Techniques

236. The main nuclear or isotopic techniques applicable to food origin testing are described in the paragraphs below. These techniques include, inter alia, stable isotope ratio analysis of heavy elements by thermal ionization mass spectrometry using thermal ionization mass spectrometry (TIMS) and multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS); multi-element analysis using inductively coupled plasma mass spectrometry ICP-MS, ICP-Optical Emission Spectroscopy (OES), X-ray fluorescence (XRF), neutron activation analysis (NAA) and related techniques. In addition, techniques such as NMR spectroscopy and mass spectroscopy for metabolite profiling or non-targeted screening, alongside other rapid nuclear methods utilized for presumptive testing such as ion mobility spectrometry (IMS) may, be used.

237. The breadth and complementary nature of these techniques provide a robust foundation for the determination of food origin and authenticity in support of food traceability systems and foods with added value. Additionally, the track record of each technology in successfully contributing to food origin and adulteration detection is critical with respect to knowledge transfer and rapid implementation and training in countries and regions currently lacking an analytical solution.

Stable Isotope Measurements

238. Nuclear techniques exploit the systematic global variations in the stable isotope ratios of the bioelements hydrogen, carbon, nitrogen, oxygen and sulphur measured using IRMS and heavy isotope variations in strontium and other biogeochemical indicators. As a first approximation, natural abundance stable isotope measurements provide information on plant photosynthesis or diet (carbon and nitrogen isotope ratios), and geographical origin (hydrogen, oxygen, sulphur and strontium isotope ratios). For example, the measurement of the ratios of naturally occurring stable isotopes of the bioelements hydrogen, carbon, nitrogen, oxygen and sulphur in foods can often provide information on the geographical origin or the production technique of the food through linkages to the ratios of the isotopes in the environment or, for example, animal feeding regimes. Strontium isotopes, measured by TIMS or MC-ICP-MS, also provide information related to the geology of the region of production, which is transferred through bioavailable fractions in soils to plants and animals. Since the stable isotope 'fingerprints' of food are intrinsically linked to the characteristics of the production area, it is not economically feasible to artificially manipulate and counterfeit them.

Elemental Profiling

239. Elemental profiling of foods using ICP-MS provides important information on the concentration of macro, micro and trace elements linking a food to its place of production and any technological

processing that potentially alters its elemental profile, such as milling or grinding. Plants possess the compositional reflection of the bioavailable and mobilized nutrients present in the underlying soils from which they were cultivated. For example, alkaline metals, especially rubidium and cesium, are easily mobilized in the soil and transported into plants, and they are consequently good indicators of geographical identity.

240. Trace element availability depends on several factors, such as soil pH, moisture and porosity, as well as clay and humus content in soil. Consequently, the range of soils present, together with bioavailability, mean that elemental composition may provide a unique combination of markers in food that characterize geographical origin and traceability. Similarly, the multi-elemental profile of animal tissue reflects, to some extent, the vegetation eaten by animals and can be linked to specific production areas, e.g. in the case of pasture-fed dairy and beef cattle. In addition, element profiling provides information on food safety with regard to the concentration of potentially toxic elements such as arsenic, cadmium, lead and mercury.

Metabolomic Fingerprinting (Metabolomics)

241. The analysis of metabolites in food is another important technique commonly used for authenticity testing. The metabolites result from cellular or molecular processes in an organism and may be characterized by NMR and mass spectroscopy. Metabolomics can be either targeted, focusing on groups of related metabolites to provide direct functional information for metabolomics modelling, or untargeted, detecting patterns in the metabolome that can differentiate between sample sets and can be used to build models for classification of unknown samples based on the metabolic pattern or fingerprint. All such techniques rely heavily on multivariate statistical analysis to process and interpret the results (Figure F-4).

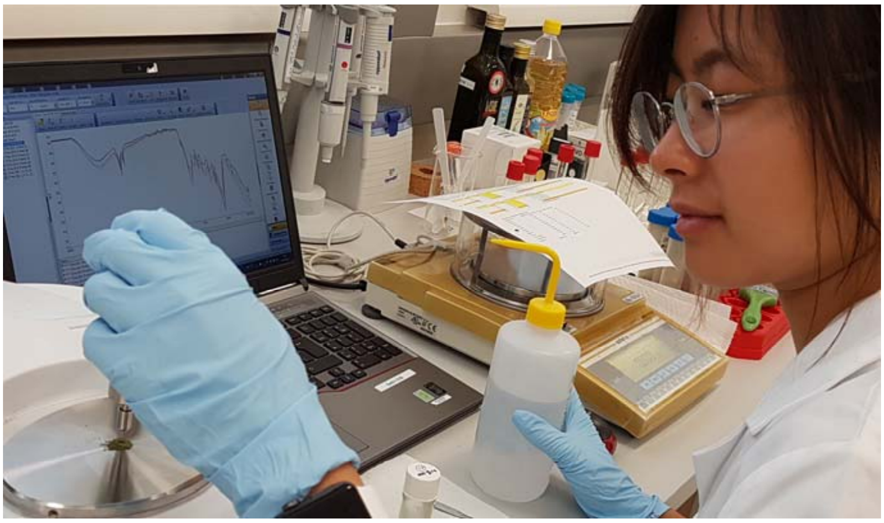

FIG. F-4. IAEA Staff Member, analysing a green tea sample (Photo: IAEA)

242. NMR and electron paramagnetic resonance can be applied to studies of complex mixtures in foods with simple or no prior separation of the components and can provide information on the geographical origin, presence of adulterants, quality and technological processing of a food. An example of the application of this type of technique is profiling using proton high-field NMR spectroscopy to determine the origin and presence of adulterants in honey, fruit juices and wines. The results of an unknown sample are compared with a database of authentic samples of known provenance, showing either a positive match, if the sample is authentic, or an abnormal fingerprint, if it is not. An additional strength of these techniques is that the region of the spectral abnormality may be further analysed to identify the chemical or chemicals used for adulteration. Furthermore, electron paramagnetic resonance characterization

provides a sensitive and accurate measurement technique for the detection of organic radical species, with unpaired electrons, under a magnetic field showing that quality assurance and safety standards are met by fruit and vegetable growers, spice producers and other similar product supply chains. Electron paramagnetic resonance confirms the use of food irradiation by detecting the antioxidants, cellulose radicals and crystalline sugar radicals in food samples. Food irradiation is the process of treating foodswith approved levels of ionizing radiation to eliminate disease-causing organisms and extend the shelf life of such foods. It is also used to ensure microbial safety to inactivate parasites and pathogenic microorganisms by eliminating insects and harmful bacteria, such as Escherichia coli in meats and poultry, often found in a wide variety of food products by applying a processing technology aimed at the improvement of food safety.

Screening Technology

243. Recent developments in analytical instrumentation are making some nuclear and electron paramagnetic techniques more portable and accessible. Various categories of instruments that were previously used only in laboratories are becoming available in more affordable benchtop, portable or hand-held versions, capable of screening foods for atypical characteristics or abnormalities. For example, relatively affordable benchtop NMR and electron paramagnetic resonance instruments have recently become available that can perform screening analyses previously run on expensive high-field MR instruments that require specialized infrastructure and dedicated personnel.

244. Similarly, portable and hand-held XRF spectrometers may find applications in food testing for elemental fingerprinting if their relative sensitivity can be improved. Another benchtop and portable technique that has great potential for food authenticity screening is headspace gas chromatography–ion mobility spectroscopy (GC–IMS), which employs a very low energy radiation source. IMS has been used extensively for many years to screen for explosives and illegal drugs at airports and is only recently being applied to food authenticity and origin confirmation by examining the volatile organic components in food. Examples include screening the authenticity and origin of dairy products, rice and high-value vegetable, seed and nut oils, e.g. Moroccan argan oil.

F.2.3. Databases

245. In order to apply the above technology to food origin and independent verification of traceability systems, it is necessary to characterize the natural variation in the SITE analysis and metabolic ‘fingerprints’ of authentic geographic indication food products over a number of annual or harvest cycles. This information can then be incorporated into a reference library or food origin database to compare suspected counterfeit or adulterated food products. Although the methodology and technology are available, the lack of existing databases and/or the limited interoperability between them is the key stumbling block for enabling the methodology to implement SITE analysis and metabolite fingerprinting for food origin and authenticity testing.

Did you know?

A food origin database is an organized collection of data, analysed with established protocols and acquired from a representative number of authentic samples.

246. The purpose of such a database is to define the natural (and permissible technological) variability of certain specific properties of a foodstuff. This ‘natural’ variability is taken as a reference for comparison when testing suspect samples or conducting routine surveillance of market samples to detect food fraud, such as mislabelling and adulteration. Considering the ultimate aim of such databases in

support of food traceability systems (e.g. targeted or compartmentalized recalls) and the implications in cases where a tested food is found not to conform, it is imperative that these databases are well supported by an independent, global and trusted host that Member States can routinely use to compare suspected fraudulent and counterfeit foods.

247. A range of nuclear and related analytical techniques are available for food origin testing to support, or independently verify, food traceability systems. Upcoming developments are expected to include further miniaturization of analytical instruments for first-tier screening, using novel and emerging technologies such as nanomaterials and advanced data-handling tools to develop portable, rapid and non-invasive instruments, which will significantly increase the numbers of food samples that can be tested. For example, prototype food scanners have already been developed using ordinary smartphones as the screening device. The cost-effectiveness and accessibility of these techniques mean that they could potentially be used to screen foods at multiple points along the food value chain by stakeholders in the food industry, regulators and even consumers, which would significantly increase the effectiveness of control systems.

248. The integration of such instruments into food testing systems is expected to trigger a paradigm shift in which laboratories applying the highly sensitive and specific nuclear and isotopic techniques that provide crucial information will move from dealing with high numbers of compliant samples to fewer, more relevant samples that have been identified as suspicious.

F.3. Nuclear Techniques for Greenhouse Gas Monitoring to Mitigate the Impact of Climate Change

F.3.1. Background

249. The emissions of major greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are contributing to global warming, which is affecting the sustainability of agricultural production systems. Recent data by the Intergovernmental Panel on Climate Change (IPCC) clearly shows that anthropogenic emissions of GHGs are at the highest in history[22]. Since 1900, the earth's average surface air temperature has increased by about 0.8°C, with most of these increases taking place since the mid-1970s. Changes in agriculture and land use contribute approximately 25% of the total GHG emissions, mainly owing to the inefficient use of chemical fertilizers and animal manure, overgrazing, and deforestation. While agriculture is contributing considerably to climate change through GHG emissions, it is also a victim of climate change because of the negative impact climate change has on the availability of water, soil fertility and quality, and crop productivity.

250. Besides direct sources, GHGs also come from different indirect sources including ammonia (NH_3) volatilization in agricultural systems (Figure F-5). A wide range of NH_3 emissions (10% to 60% of the applied nitrogen) have been reported in different agro-ecosystems[23]. Such heavy NH_3 losses from agriculture have agronomic, environmental and economic implications. For example, emitted NH_3 causes health and environmental problems, including inflammation of the respiratory system, eutrophication of water and acidification of soil. Additionally, NH_3 acts as a secondary source of N_2O, a powerful greenhouse gas contributing to global warming. In addition, the spatial and temporal variability of GHG emissions poses major challenges for their measurement and management within and across various agro-ecosystems and land uses, as well as the latter's inherent spatial heterogeneity.

[22] IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.IPCC, 2019. Publications [WWW Document]. IPCC - Task Force on National Greenhouse Gas Inventories. URL https://www.ipcc-nggip.iges.or.jp/public/index.html

[23] Zaman, M., Saggar, S., Stafford, A.D., Mitigation of ammonia losses from urea applied to a pastoral system: The effect of nBTPT and timing and amount of irrigation, Proceedings of the New Zealand Grassland Association 75 (2013) 209–214.

Isotopic techniques provide the tools to identify emission pathways and, in turn, provide information on effective mitigation techniques.

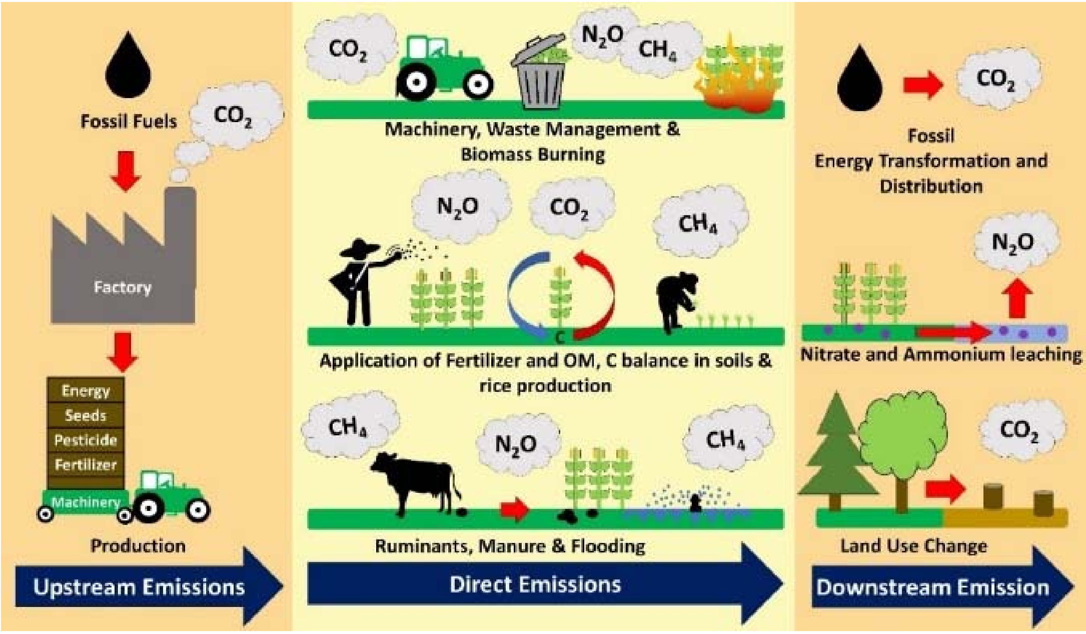

FIG. F-5: Schematic representation of direct (from the cropping system) and indirect (upstream and downstream) GHG emissions from crop production.

F.3.2. Upscaling ^{13}C Technology to the Field

251. Innovation in the field of ^{13}C now allows us to upscale carbon cycling studies from small-scale laboratory experiments to field level. For this upscaling, advanced tools for real-time ^{13}C analysis, such as the laser CO_2 carbon isotope analyser, are essential.[24] Additionally, by labelling plant material with ^{13}C isotopes, it is possible to assess the turnover of soil organic matter and its sequestration and stabilization in agroecosystems. The Agency's Soil and Water Management and Crop Nutrition Laboratory has been conducting research and development on CO_2 emissions, and the ^{13}C-labelled plant materials are now available to Member States. These technological tools, based on the use of ^{13}C isotopes, will not only help improve climate change resilience of land management, but also help understand how future climate scenarios (temperature change, different rainfall) will further affect carbon storage and CO_2 emission. These techniques provide an unambiguous estimate of how much carbon is sequestered in the soil or is released from various soil carbon pools.[25]

F.3.3. The Nitrogen-15 Tracing Technique for N_2O Measurement and Identifying N_2O Sources

252. To understand N_2O emissions, it is very important to quantify the loss of nitrogen via dinitrogen (N_2) emissions, a non-greenhouse gas which is emitted in much greater quantities than N_2O. To precisely measure GHG emissions from soils, scientists from the Joint FAO/IAEA Programme of Nuclear

[24] Müller, C., et al., Quantification of N_2O emission pathways via a ^{15}N tracing model, Soil Biology and Biochemistry 72 (2014) 44–54.

[25] Keidel, L., et al., Depth-dependent response of soil aggregates and soil organic carbon content to long-term elevated CO_2 in a temperate grassland soil, Soil Biology and Biochemistry 123 (2018) 145–154.

Techniques in Food and Agriculture and Justus Liebig University Giessen, Germany, worked together and conducted numerous laboratory and field experiments. The outcome of these studies was the development of a nitrogen-15 (^{15}N) tracing technique, which is different from the isotopic dilution technique and can precisely measure GHG emissions and identify their source in soil in short- and long-term field studies.[26, 27]

253. Recent work has highlighted the importance of isotopic techniques that provide insight into the movement and fate of nitrogen and carbon in our agro-ecosystems with regard to their storage in soils and emission into the atmosphere. The understanding of the complex nature of soils and the interacting factors contributing to soil fertility and GHG production is a prerequisite for developing climate-smart agriculture practices. Figure F-6 provides an example of results from such a trace method to quantify the N_2O pathways from a permanent grassland. Similar methods are available to identify the production and consumption processes of CH_4 and CO_2 via the application of suitable ^{13}C sources.

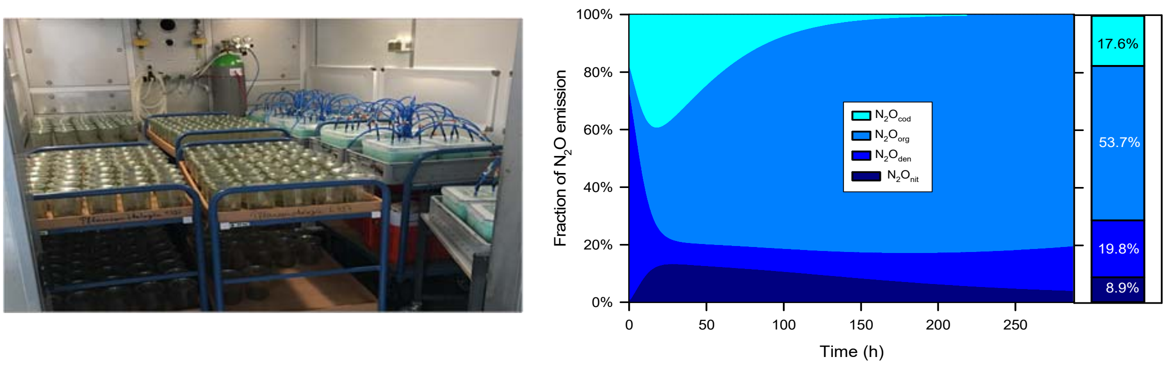

FIG. F-6: Laboratory incubation setup of a ^{15}N tracing study (left) and results from a ^{15}Ntracing study to identify the N_2O emissions pathways from a permanent grassland; N_2O_{nit} = nitrification, N_2O_{den} = denitrification, N_2O_{org} = heterotrophic nitrification, N_2O_{cod} = codenitrification. (Source: Müller et al. (2014). [28]

F.3.4. New Developments in NH_3 Measurements at Field Scale

254. The lack of inexpensive and low-tech measuring techniques has meant that only limited field studies have been conducted to measure NH3 losses worldwide. Several sophisticated methods are already available, such as wind tunnels, cavity ring down spectroscopy and micrometeorological techniques. However, these techniques are expensive and require highly skilled field technicians to operate them. This makes them inaccessible for many developing countries and institutions wishing to measure NH3 losses in different agricultural management systems.

255. To develop a low-cost and a robust method for NH_3 measurement, the IAEA worked together with the Brazilian Agricultural Research Corporation (Embrapa) and the Agronomic Institute of Paraná (IAPAR), to develop a simple NH3 chamber using a plastic bottle (Figure F-7).

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[26] Müller, C., et al., Quantification of N_2O emission pathways via a ^{15}N tracing model. Soil Biology and Biochemistry 72 (2014) 44–54.

[27] 26: Moser, G., et al., Explaining the doubling of N2O emissions under elevated CO2 in the Giessen FACE via in-field 15N tracing. Global Change Biology 24 (2014) 3897–3910.

[28] Müller, C., et al., Quantification of N_2O emission pathways via a ^{15}N tracing model, Soil Biology and Biochemistry 72 (2014) 44–54.

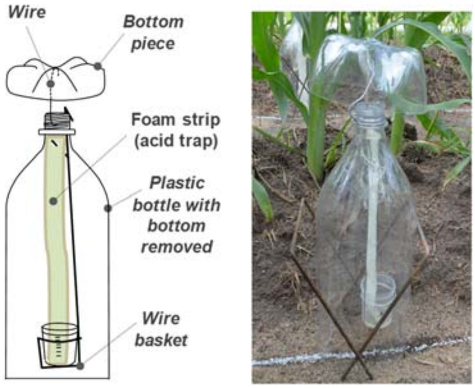

FIG. F-7: A view of the simple open chamber used to measure NH3 volatilization. Details of this chamber were described by Araújo et al. (2009) [29] *and Jantalia et al. (2012)*[30].

256. To test and confirm the accuracy of this newly developed method of measuring NH_3, the ^{15}N method was used. The ^{15}N-labelled urea was applied to the surface of lysimeters installed in the space between rows of maize crops. Open chambers made from PET bottles (Figure F-7) were installed on each lysimeter with four different rates of nitrogen application, with various distances between the chamber and the soil surface, and with or without relocation of the chamber (static vs dynamic) during the monitoring period.

257. The use of this simple open-chamber method is a suitable and reliable technique to quantify NH_3 volatilization losses from agricultural soils, and each chamber costs less than $1 USD to build. This new method of NH_3 measurement is being rolled out for use by both developed and developing countries to help monitor and respond to the environmental impact of NH_3 emissions from the livestock and agriculture industries. Its efficiency was compared with several other existing methodologies in the field using the ^{15}N technique, which produced very similar results. As a result, it is rapidly gaining recognition for its practicality, accuracy and reliability, and has been successfully used by scientists in Brazil, Chile, China, Costa Rica, the Islamic Republic of Iran, Pakistan, Spain and the United States of America. The device can precisely measure NH_3 losses in order to follow climate-smart agricultural practices to broaden the reduction of greenhouse gases and the impact on the environment.

F.3.5. Looking Forward

258. With these advancements in measurement tools and modelling, further research and development activities are envisioned in experimenting in the field, as well as in furthering concrete applications at the agro-ecosystem level. A new CRP on this topic will be initiated in 2020 to further improve the understanding of the complex processes of GHG emissions and to develop more mitigation options for reduction of GHGs, as well as options for carbon sequestration.

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[29] Araújo, E.S., et al., Calibration of a semi-opened static chamber for the quantification of volatilized ammonia from soil, Pesquisa Agropecuária Brasileira 44(7) (2009) 769–776.

[30] Jantalia, C.P., et al., Nitrogen source effects on ammonia volatilization as measured with semi-static chambers, Agronomy Journal 104(6) (2012) 1595–1603.

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