NUCLEAR TECHNOLOGY REVIEW

2018

IAEA
International Atomic Energy Agency

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Nuclear Technology Review 2018

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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 2018* covers the following select areas: power applications, advanced fission and fusion, accelerator and research reactor applications, nuclear techniques in food, soil and livestock management, with reference to emergency response, new developments in radiotherapy and neuropsychiatry, plastic pollution in oceans and radiopharmaceuticals.

The draft version was submitted to the March 2018 session of the Board of Governors in document GOV/2018/2. This final version was prepared in light of the discussions held during the Board of Governors and also of the comments received by Member States.

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Executive Summary

1. At the end of 2017, the 448 operating nuclear power reactors had a global generating capacity of 392 GW(e), which was an increase of about 1.2 GW(e) since 2016. In 2017, five reactors were permanently shut down, four were connected to the grid, and construction started on four. Near and long term growth prospects remained centred on Asia, which is home to 40 of the 59 reactors under construction, as well as 51 of the 59 reactors that were connected to the grid since 2005.

2. Thirty countries currently use nuclear power and 28 are considering, planning or actively working to include it in their energy mix. Three newcomer countries are building their first nuclear power plants (NPPs) and several others that have decided to introduce nuclear power are at advanced stages of infrastructure preparation. The Agency's 2017 high projections for global nuclear power capacity show a 42% increase over current levels by 2030 and a doubling of capacity by 2050, while in the low projections, capacity will gradually decline until 2040, rebounding to today's levels by 2050.

3. The advantages of nuclear power in terms of climate change mitigation, energy security, environmental and socio-economic policies are key reasons why many countries intend to introduce nuclear power or expand existing programmes. The Agency's International Ministerial Conference on Nuclear Power in the 21st Century, held in Abu Dhabi, stressed that substantial nuclear power growth was needed for the world to meet its climate and sustainable development goals.

4. World uranium production in 2017 was similar to 2016 levels at about 63 000 tonnes. Low prices considerably restricted the ability of companies to raise funds for exploration, feasibility studies and construction of new projects of expansion. Global uranium resources, conversion, enrichment and fuel fabrication capacities are more than adequate to meet the demand.

5. The IAEA Low Enriched Uranium (LEU) Bank Storage Facility in Kazakhstan was inaugurated in August 2017. The request for proposals for LEU acquisition was issued in November 2017.

6. Progress continued to be made in strengthening and improving safety at NPPs across the world. The most common challenges include implementation of organizational changes, delays in commissioning activities, human capacity building, optimization of maintenance activities, assessment of major plant safety modifications, strengthening accident management and on-site emergency preparedness and response, as well as leadership and management for safety. The Agency, with its safety standards and improved tools and materials, continued to assist and guide Member States in those areas.

7. To date, around 400 000 tonnes of heavy metal have been discharged from NPPs as spent nuclear fuel, of which about 25% is being reprocessed. There are 151 away-from-reactor dry spent fuel storage facilities in 27 countries.

8. In the years to come considerable decommissioning work around the world on power reactors, research reactors, critical assemblies and other fuel cycle facilities is expected.

9. Several countries made progress in their projects on deep geological disposal of high level radioactive waste and/or spent fuel declared as waste and on borehole disposal projects for disused sealed radioactive sources. Disposal facilities for all other categories of radioactive waste are operational worldwide.

10. Research and development (R&D) on and deployment of advanced fission reactors continued in several Member States. Most newcomers look at advanced water cooled reactors with increased power outputs for their first reactors. Several fast reactor technologies, built on decades-long design, construction and operation experience, are under deployment and development. Many Member States, including newcomers, are working on developing gas cooled reactors, with increased safety and

efficiency characteristics. Over 50 small and medium sized or modular reactors of all major reactor types are under development, of which three are in advanced stages of construction. These activities are supported by several international initiatives on innovative nuclear energy systems.

11. There is increased interest in using nuclear energy for non-electric applications in seawater desalination, hydrogen production, district heating, tertiary oil recovery and other industrial applications. Cogeneration can offset a significant part of nuclear power generation costs.

12. Significant progress is visible at the International Thermonuclear Experimental Reactor (ITER) site and a wide ranging fusion R&D programmes are under way in several Member States. Another key milestone in fusion energy has been the production of the first plasma at the optimized stellarator Wendelstein 7-X.

13. Accelerators continued to serve for environmental studies, biomedical applications, materials science, cultural heritage characterization, provenancing and radiocarbon dating. Having emitted its “first light” early in 2017, the first synchrotron light source in the Middle East, SESAME, was inaugurated.

14. The 238 research reactors in operation in 56 countries continue to play a strategic role in supporting medical, industrial, educational and nuclear power sectors. Seven countries are constructing new research reactors, while several others are planning or considering building new ones, as key national facilities for the development of nuclear science and technology infrastructure and programmes, including nuclear power. Two new research organizations became IAEA-designated International Centre based on Research Reactor (ICERR) in 2017.

15. To date, 97 research reactors and 2 medical isotope production facilities have been converted from the use of high enriched uranium (HEU) to LEU or confirmed as shutdown. Further work is necessary to achieve the commercial availability of high density LEU fuels to convert high flux, high performance research reactors. HEU minimization activities, including the return of HEU research reactor fuel to the country of origin, continued in 2017. The three-year project to convert the only research reactor in Ghana from HEU fuel to LEU fuel saw its completion in 2017, when HEU fuel was repatriated to China.

16. Despite challenges resulting from occasional reactor outages, the global supply of Molybdenum-99, the most used medical isotope, has been maintained through excellent cooperation and pre-emptive actions collectively taken by the major international producers, supply chain coordinating bodies, government stakeholders and involved research reactors.

17. As part of nuclear or radiological emergency preparedness, the rapid identification capability is considered essential to prevent potentially contaminated agricultural products from reaching consumers. Many agencies may be involved in an emergency response and the efficient management and interpretation of large sets of data will be critical for appropriate decision making. There are new developments in IT decision support system (DSS) tools that allow for the improved real-time management of large volumes of data and integrated decision-making support in spatial and temporal terms. However, there are not many tools that focus on securing decisions made for food and agriculture. To this end, the Agency has developed DSS4NAFA, a comprehensive cloud-based tool that optimizes collection, management and visualization of agriculture-related data. Upon obtaining the radionuclide concentration data, the tool can suggest food and planting restrictions based on the level of risk and specific tolerance levels. The beta version of the tool will become available in 2018.

18. Research on the irradiation of pathogens to create vaccines has been under way since the 1950s, but over-irradiation often destroys the nucleic and protein structures of the vaccines. Modern irradiators can generate higher and more specific doses in an effective manner, which, together with advances in

genomic research and better knowledge of immune systems, has opened the field to the development of a new range of vaccines. Current developments in irradiated vaccine technologies are demonstrating the potential to produce new vaccines against many disease-causing viruses, parasites and bacteria that can have a significant positive effect on animal and human health and economies in developing countries.

19. Agricultural pollution of rivers and streams has a negative impact on human health, biodiversity and fisheries. As pollutants can originate from multiple sources, multiple approaches are required to formulate a clear characterization of the origin and transport of solutes through soil. The stable isotopes of nitrogen, carbon, oxygen, sulphur and hydrogen can all be used as tracers to provide this information in agro-ecosystems. The isotopic element of each element is unique and thus can be used to fingerprint, often overlapping, sources. Research using multiple stable isotope tracers, when integrated with conventional techniques will present a clear picture of multiple polluting pathways, and the information provided will help to increase the sustainability of land management practice.

20. Stereotactic radiotherapy is a non-surgical, advanced radiation technique to treat cancer by delivering precisely targeted radiation to tumours, avoiding the considerable risks associated with invasive surgery, particularly for difficult to reach areas or those close to vital organs. The system involves 3-dimensional imaging and 4-dimensional tumour localization, and highly focused gamma-ray or X-ray beams. With a linear accelerator, large tumours can be treated in a single session. The technique can be used to treat many functional disorders of the brain, early stage lung cancer, and prostate, pancreas, liver and kidney cancers, as well as head, neck and spinal cancers, in medically inoperable patients. Clinical trials indicate that stereotactic radiotherapy may emerge as a cost effective treatment compared to conventional radiotherapy in many clinical settings.

21. Dementia comes in many forms, with Alzheimer’s disease being the most common. Distinctive clinical symptoms can be hard to diagnose in the early stages. However, nuclear techniques are now becoming instrumental in identifying the underlying disease process, sometimes years before symptoms are noticeable, allowing for appropriate and differential diagnoses. Nuclear medicine, also known as molecular imaging, can diagnose various brain disorders and differentiate symptoms caused by neurodegenerative dementia and other conditions with similar symptoms such as strokes. In addition, radiotracers can offer reliable biomarkers in dementia, assisting clinicians to diagnose different dementing disorders. The advances being made through neuroimaging are providing critical knowledge of the disease process that will help improve therapeutic developments.

22. The ocean has become the final repository for much land-originating pollution including plastics. The particular effects of micro-plastics on marine organisms can now be better understood through research using nuclear and isotopic techniques. Micro-plastics cause adverse effects through simple ingestion and can also become deposited in internal organs where they may be effective vectors for further contaminant transfer, including to humans. Current research is addressing the fate and toxicity of micro-plastics and associated contaminants in socially and economically important marine species.

23. Therapeutic radiopharmaceuticals have been used to kill cancer cells for several decades. However, the beta particles that have been used travel much further than alpha particles of the same energy. It is this distinction that allows precision of alpha particles in the targeting of cancerous cells with much less risk of damaging other tissue beyond or around the targeted zone. Various alpha emitter radionuclides are being evaluated at pre-clinical and clinical levels to determine their potential for use as radiopharmaceuticals, which will further advance the treatment of cancer.

24. During 2017 the Renovation of the Nuclear Applications Laboratories project recorded several significant milestones. The new Insect Pest Control Laboratory was inaugurated and work began on a Flexible Modular Laboratory in Seibersdorf. Further extra-budgetary funds were raised during the year, bringing the overall financial contributions to the modernization from 31 Member States and other

contributors to nearly €32.5 million. Efforts aimed at extending the Agency’s partnerships and resource mobilization base beyond its traditional partners resulted in a partnership concluded with Varian Medical Systems for a ten-year loan of a linear accelerator (LINAC) to the Dosimetry Laboratory, complemented by an in-kind contribution by a Member State for its support services. The Agency signed a Memorandum of Cooperation with the Shimadzu Corporation for the donation of a liquid chromatograph, through the Peaceful Uses Initiative, for activities to better support Member States in the area of research on food safety and training.

Nuclear Technology Review 2018

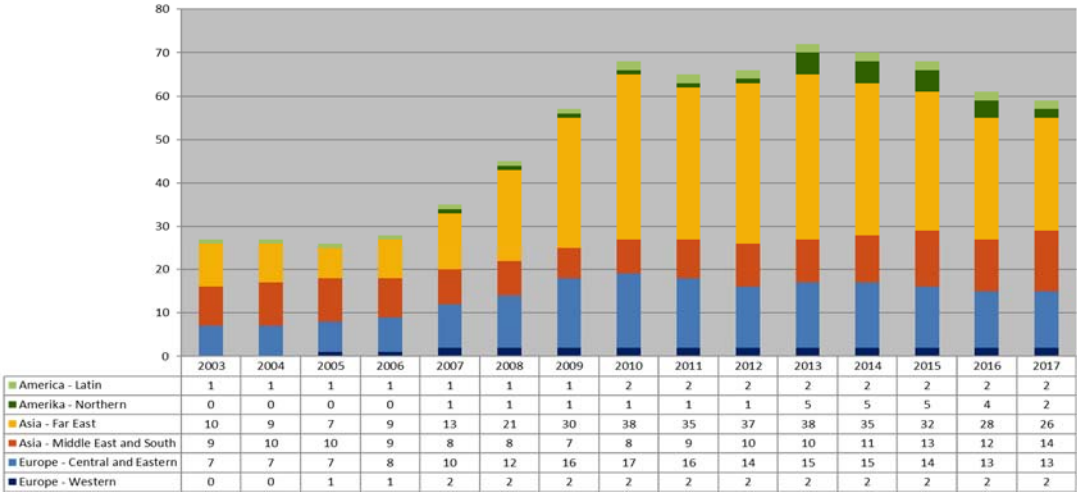
Main Report

A. Power Applications

A.1. Nuclear Power Today

1. As of 31 December 2017, there were 448 operational nuclear power reactors worldwide, with a total capacity of 392 GW(e)[1] (see Table A-1). This represents an increase of some 1.2 GW(e) in total capacity, compared to 2016. Of the operational reactors, 81.9% are light water moderated and cooled, 10.9% are heavy water moderated and cooled, 3.3% are light water cooled and graphite moderated, and 3.1% are gas cooled reactors. Three are liquid metal cooled fast reactors. Nearly 89% of nuclear generated electricity was produced by 370 light water reactors.

2. In 2017, four new pressurized water reactors (PWRs) were connected to the grid: three in China (Fuqing-4, Tianwan-3, Yangjiang-4), one in Pakistan (CHASNUPP-4). Five reactors were permanently shut down: Kori-1 (Republic of Korea), Oskarhamn-1 (Sweden), Santa Maria de Garoña (Spain), Monju (Japan) and Gundremmingen-B (Germany). Monju and Santa Maria de Garoña had been in long term shutdown before being declared as permanently shut down.



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
🟩 America - Latin	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
■ Amerika - Northern	0	0	0	0	1	1	1	1	1	1	5	5	5	4	2
🟨 Asia - Far East	10	9	7	9	13	21	30	38	35	37	38	35	32	28	26
🟧 Asia - Middle East and South	9	10	10	9	8	8	7	8	9	10	10	11	13	12	14
🟦 Europe - Central and Eastern	7	7	7	8	10	12	16	17	16	14	15	15	14	13	13
■ Europe - Western	0	0	1	1	2	2	2	2	2	2	2	2	2	2	2

FIG. A-1. Number of reactors under construction by region.
(Source: IAEA Power Reactor Information System http://www.iaea.org/pris*)*

3. As of 31 December 2017, 59 reactors were under construction. Construction started on Shin-Kori-5 (Republic of Korea), Kudankulam-3 and 4 (India) and Rooppur-1 (Bangladesh). Expansion, as well as near and long term growth prospects, remains centred in Asia (Figure A-1), where 40 reactors are under construction. Asia is also home to 51 of the 59 new reactors that have been connected to the grid since 2005.

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

Table A-1. Nuclear power reactors in operation and under construction in the world (as of 31 December 2017)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2017		Total Operating Experience through 2017	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	3	1 633	1	25	5.7	4.5	82	2
ARMENIA	1	375			2.4	32.5	43	8
BANGLADESH			1	1 080				
BELARUS			2	2 220				
BELGIUM	7	5 918			40.2	49.9	289	7
BRAZIL	2	1 884	1	1 340	14.9	2.7	53	3
BULGARIA	2	1 926			14.9	34.3	163	3
CANADA	19	13 554			95.1	14.6	731	6
CHINA	39	34 514	18	19 016	232.8	3.9	280	9
CZECH REPUBLIC	6	3 930			26.8	33.1	158	10
FINLAND	4	2 769	1	1 600	21.6	33.2	155	4
FRANCE	58	63 130	1	1 630	381.8	71.6	2 164	4
GERMANY	7	9 515			72.2	11.6	832	7
HUNGARY	4	1 889			15.2	50.0	130	2
INDIA	22	6 255	7	4 824	34.9[b]	3.2	482	11
IRAN, ISLAMIC REPUBLIC OF	1	915			6.4	2.2	6	4
JAPAN	42	39 752	2	2 653	29.3	3.6	1 823	5
KOREA, REPUBLIC OF	24	22 494	4	5 360	141.3	27.1	523	5
MEXICO	2	1 552			10.6	6.0	51	11
NETHERLANDS	1	482			3.3	2.9	73	0
PAKISTAN	5	1 318	2	2 028	8.1	6.2	72	5
ROMANIA	2	1 300			10.6	17.7	31	11
RUSSIAN FEDERATION	35	26 142	7	5 520	190.1	17.8	1 261	9
SLOVAKIA	4	1 814	2	880	14.0	54.0	164	7
SLOVENIA	1	688			6.0	39.1	36	3
SOUTH AFRICA	2	1 860			15.1	6.7	66	3
SPAIN	7	7 121			55.6	21.2	329	1
SWEDEN	8	8 629			63.1	39.6	451	0
SWITZERLAND	5	3 333			19.6	33.4	214	11
UKRAINE	15	13 107	2	2 070	80.4	55.1	488	6
UNITED ARAB EMIRATES			4	5 380				
UNITED KINGDOM	15	8 918			63.9	19.3	1 589	7
UNITED STATES OF AMERICA	99	99 952	2	2 234	805.6	20.0	4 309	9
Total[c, d]	448	391 721	59	60 460	2 503.1		17 430	6

a. Data are from the Agency's Power Reactor Information System (PRIS) (http://www.iaea.org/pris);

b. Electricity data for India is based on the provided annual country level value, as data from some reactors were not available at the time of the issuance of this report.

c. Note: The total figures include the following data from Taiwan, China;
6 units, 5052 MW(e) in operation; 2 units, 2600 MW(e) under construction;
35.1 TW·h of nuclear electricity generation, representing 16.3% of the total electricity generated.

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 Taiwan, China (206 years, 1 month);

A.1.1. Newcomers

4. Among the 28 Member States that have expressed interest in nuclear power, 19 have initiated studies on nuclear power infrastructure, 4 have already taken a decision and are preparing the necessary infrastructure, and 5 have signed contracts and are preparing for or have already commenced construction. Another 21 Member States are expected to continue working towards making a decision to establish a nuclear power programme within the next decade.

5. In the United Arab Emirates, construction continued on all four reactors of the country's first nuclear power plant (NPP), located at Barakah. Unit 1 is scheduled to start operation in 2018, and followed by the other three in the following years. The Agency conducted Education and Training Appraisal and Pre-Operational Safety Review Team missions in 2017. In Belarus, construction of the first NPP at Ostrovets was under way, with commissioning of the two units scheduled for 2019 and 2020. The final safety analysis report was submitted for regulatory review in 2017. An Agency Site and External Events Design mission was hosted in 2017.

6. In Bangladesh, safety-related construction at Unit 1 of the Rooppur NPP started on 30 November. The two Rooppur units are expected to be commissioned in 2023 and 2024. In Turkey, non-nuclear construction work at Akkuyu started in October, based on a limited construction licence, with commissioning of Unit 1 planned for 2023. Egypt completed negotiations with the State Atomic Energy Corporation "Rosatom" of the Russian Federation on four key agreements for the construction of the four-unit NPP at El Dabaa, planned to be completed between 2023 and 2026.

7. Negotiations between Jordan and Rosatom have progressed. With the key grid study and cooling water studies completed, a final investment decision is expected in 2018. Nigeria signed agreements in October 2017 with the Russian Federation on the construction and operation of an NPP and a nuclear research centre, and a roadmap for cooperation on peaceful nuclear technologies. Poland and Saudi Arabia worked on international tenders, and plan to issue them in 2018. Kenya's decision on a nuclear power programme is pending.

8. Member States continue to take benefit of the Agency's assistance in developing the necessary national nuclear infrastructure, based on the Milestones approach, which supports the establishment of safe, secure and sustainable nuclear power programmes. This involves peer review and expert missions, training courses and tools that systematically cover the 19 nuclear infrastructure issues. With the Integrated Nuclear Infrastructure Review (INIR) mission conducted in Ghana in 2017, the number of INIR missions deployed since its launch in 2009 reached 22 in 16 Member States.

A.1.2. Expanding Countries

9. With 38 nuclear power reactors in operation and 19 under construction, China continues to have the largest expansion programme and has plans to build 30 reactors overseas by 2030.

10. The Olkiluoto-3 EPR project in Finland has moved to the commissioning phase, with cold functional tests completed. Following hot functional tests, commercial operation is planned to start in early 2019. The Hanhikivi-1 project remains under licensing review, with plans to start construction in 2019.

11. In March 2017, the construction of new units at the Paks II nuclear power plant was approved by the European Commission, and, in April 2017, the Hungarian Atomic Energy Agency issued a final environmental licence and a licence for the NPP site.

12. In September 2017, the first of three steam generators was installed at Pakistan's Karachi Unit 2, which is the first of two Chinese Hualong One reactors under construction at the site. (Figure A-2)

FIG. A-2. Construction works at Karachi Unit 2, Pakistan, September 2017.
(Photo: China Nuclear Engineering Corporation — CNEC)

13. Non-safety-related construction works began at Bushehr-2, the Islamic Republic of Iran, in March. The VVER-1000 unit is planned to be completed in 2024, with Bushehr-3 to follow in 2026.

14. In the USA, construction continued at the AP1000 Vogtle-3 and 4 with Southern Nuclear taking over the project management from Westinghouse; operation is planned to start in 2021 and 2022 respectively. The construction of Summer-2 and 3, also AP1000 reactors, was suspended in July 2017 due to economic reasons.

15. In May, Argentina's state nuclear company, Nucleoeléctrica, signed agreements with the China National Nuclear Corporation (CNNC) for two new reactors: Construction of a new 720 MW(e) Candu reactor is planned to start in 2018, followed by a 1000 MW(e) Hualong One unit in 2020.

16. In August, India signed contracts with Rosatom on Units 5 and 6 of Kudankulam NPP, both VVER-1000 type reactors, to be built in collaboration with the Nuclear Power Corporation of India.

17. In October, South Africa's Department of Environmental Affairs granted an environmental authorization for the construction and operation of a 4000 MW(e) NPP with associated infrastructure at Duynefontein, near the operating Koeberg NPP.

A.1.3. Operating Countries

18. At the end of 2017, 47% of the 448 operating nuclear power reactors had been in operation for 30 to 40 years, and another 17% for over 40 years. Long term operation and ageing management programmes are being implemented for an increasing number of NPPs.

19. To meet its industrial strategy for safely operating the existing nuclear power plant fleet for well beyond 40 years, Électricité de France (EDF) has launched its 'Grand Carénage' programme, which involves a major plant refurbishment programme to improve performance and safety. It is expected to run for ten years. As for the replacement of part of France's existing fleet, the Flamanville-3 EPR is in the commissioning phase, with cold functional tests completed. Following hot functional tests, commercial operation is scheduled to begin at the end of 2018.

20. Renewal of licences for operating NPPs in the USA is a mature, stable process, with 86 of the 99 reactors possessing renewed licences for operation up to 60 years. Under the same regulatory process as for initial licence renewal, the US Nuclear Regulatory Commission (NRC) issued guidance documents in July 2017 for subsequent licence renewal for plant operation up to 80 years.

21. Kozloduy 5 and 6 reactors in Bulgaria had operational licences until 2017 and 2019. In November 2017, by extending Unit 5's licence to 2027, the Bulgarian Nuclear Regulatory Agency for the first time permitted continued operation of a nuclear reactor beyond its original operating licence.

22. Japan's 42 operable reactors, five have so far cleared inspections confirming that they meet the new regulatory safety standards and have resumed operation. These are: Kyushu's Sendai-1 and 2; Shikoku's Ikata-3; and Kansai's Takahama-3 and 4. Another 20 reactors have applied to restart.

23. The operational safety of NPPs remains high, as shown by safety indicators collected by the Agency and the World Association of Nuclear Operators. Figure A-3 shows the number of unplanned manual and automatic scrams or shutdowns per 7000 hours (approximately one year) of operation per unit. Scrams are just one of several possible, but commonly used, safety performance indicators.

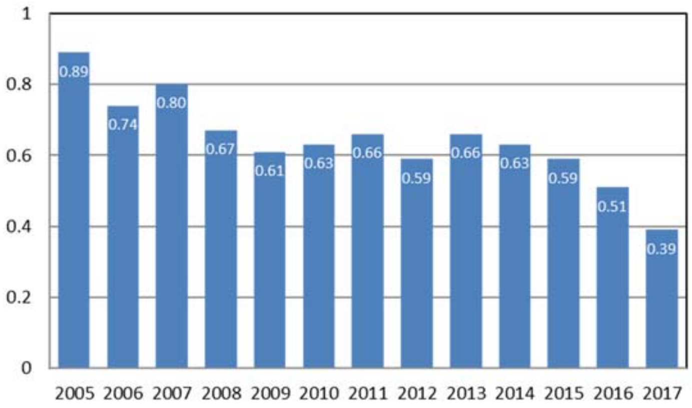

FIG. A-3. Mean rate of scrams: the number of automatic and manual scrams per 7000 hours of operation of a unit (Source: IAEA Power Reactor Information System: www.iaea.org/pris).

A.2. The Projected Growth of Nuclear Power

24. According to the Agency's 2017 projections (Figure A-4), world nuclear electrical generating capacity is expected to grow to 554 GW(e) by 2030 and to 874 GW(e) by 2050 in the high case scenario. This represents a 42% increase over current levels by 2030 and a doubling of capacity by 2050. In the low case scenario, capacity is projected to decline gradually until 2040, rebounding to about today's level by 2050.

25. The wide range in these projections is partly due to the considerable number of reactors scheduled for retirement around 2030 and beyond, particularly in North America and Europe, and uncertainty concerning whether new nuclear capacity would be built to replace them.

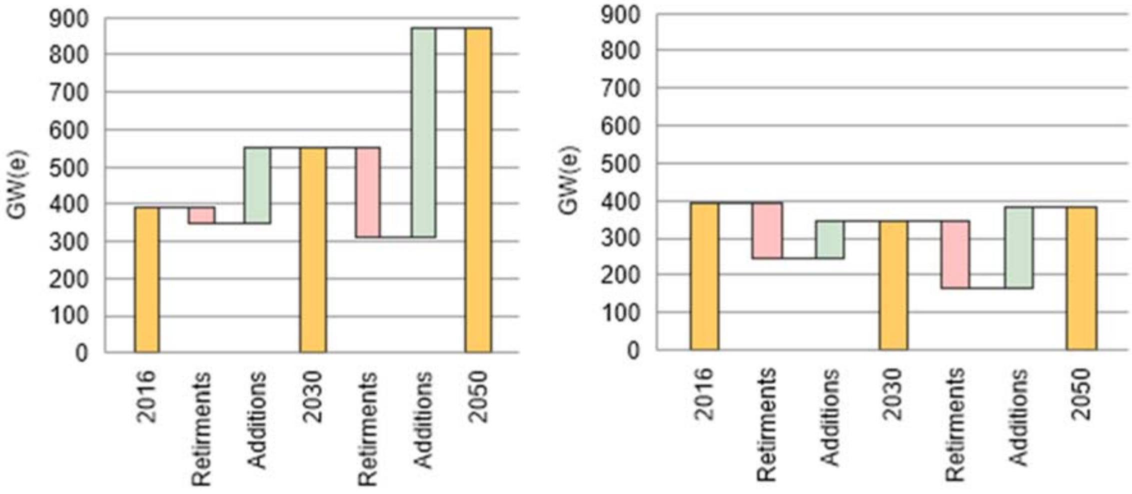

FIG. A-4. High (left) and low case projections for world nuclear capacity. (Source: Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, IAEA Reference Data Series No. 1, 2017).

26. The high case scenarios of the IAEA, the Organisation for Economic Co-operation and Development's (OECD's) International Energy Agency (IEA) and the World Nuclear Association (WNA) consistently show growth in the range of 500–600 GW(e) by 2030, while the low case scenarios reflect larger growth uncertainties (Figure A-5).

27. Nuclear power makes a significant contribution to reducing greenhouse gas emissions worldwide, while fulfilling the increasing energy demands of a growing population and supporting sustainable development. Nuclear reactors produce virtually no greenhouse gas emissions or air pollutants during operation and only very low amounts during their entire life cycle. Hence, the use of nuclear power avoids the emission of nearly 2 billion tonnes of carbon dioxide every year.

28. The Paris Agreement, ratified by 171 countries, calls on countries to limit the rise of global average temperature to well below 2°C above pre-industrial levels. The findings of the IAEA, IEA and WNA highlight the need for increased use of nuclear power in the longer term to reach the 2°C goal. Its advantages in climate change mitigation, as well as energy security and non-climatic environmental and socio-economic benefits, are important reasons why many countries, particularly in the developing world, intend to introduce nuclear power in the coming decades, or to expand existing programmes.

29. The Agency's International Ministerial Conference on Nuclear Power in the 21st Century, held in Abu Dhabi from 31 October to 2 November 2017. National statements and panel discussions focused on nuclear power for solving the 3Es (energy–economy–environment) trilemma, challenges in developing nuclear power infrastructure, safety and reliability aspects of nuclear energy, and innovations and advances in nuclear technologies. The Conference highlighted that substantial nuclear power growth was needed for the world to meet its sustainable development and climate goals.

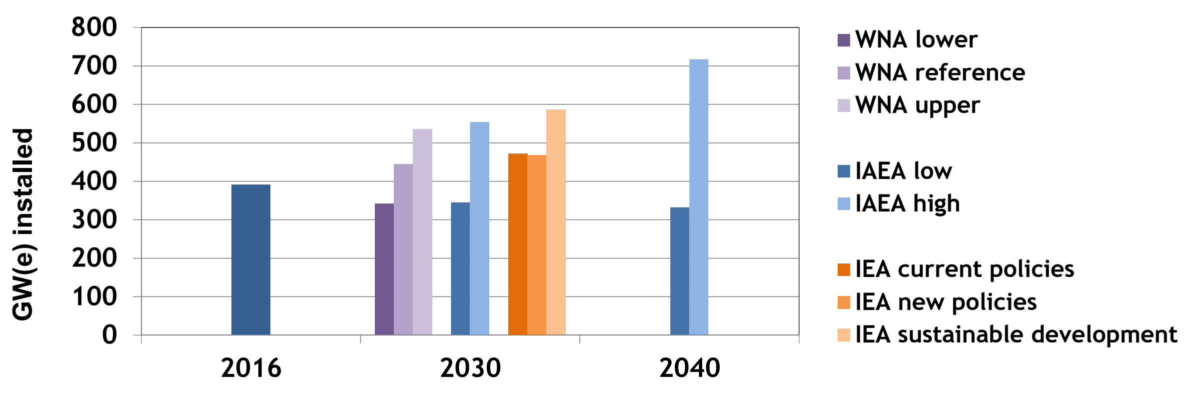

FIG. A-5. Comparison of the IAEA's 2017 projection for nuclear power capacity with the IEA's scenarios and the WNA's projections (IEA figures are based on gross capacity).

A.3. Fuel Cycle

A.3.1. Front End

Uranium Resources and Production

30. Uranium spot prices remained depressed in 2017, generally staying within the range of $42/kgU to $54/kgU. Reduced prices considerably restricted the ability of companies to raise funds for exploration, feasibility studies and construction of new expansion projects. Thus, world production in 2017 is likely to be similar to that of 2016, which was 63 366 tonnes of uranium (tU), compared to 60 496 tU in 2015.

31. Kazakhstan maintained its place as the world's leading uranium producer, almost entirely from its in situ leach mines. After rapidly increasing production between 2000 and 2012, and with a production of 23 800 tU in 2015 and 30 062 tU in 2016, a similar figure is expected for 2017.

32. In Canada, the second largest producer, the annual 5000 tU/year production capacity of Cigar Lake (the world's highest grade uranium mine that began commercial production in May 2015) is expected to increase to 6900 tU/year by the beginning of 2018.

33. Husab uranium mine in Namibia commenced commercial production in 2016, producing 192 tU for the year. The output is expected to rise, and the full capacity could be 5770 tU/year, with a forecast life of over 20 years. Namibia's Rössing and Langer Heinrich uranium mines continued operations over 2017. Low-key feasibility work continued at some other Namibian uranium deposits.

34. In Australia, the Four Mile in situ leach uranium mine produced approximately 1400 tU/year. At the Ranger project, production in 2016 was 1994 tU, with 1700−2000 tU expected in 2017, compared to 4000 to 6000 tU/year between 1997 and 2009. Under current arrangements, mining and processing must cease by January 2020 and rehabilitation finalized within five years. The Olympic Dam copper–uranium–gold–silver mine continued conventional operations, whilst the option of heap leaching of a portion of its ore continued to be trialled. Studies and approvals were progressed for several uranium deposits in Western Australia, but with no firm construction and opening dates.

35. Feasibility and environmental studies and approvals continued for the rare earth, base metals and uranium project at the Kvanefjeld deposit in Greenland, Kingdom of Denmark.

36. China continued to show a strong commitment to nuclear growth through uranium exploration and development expenditures, both nationally and abroad. Development expenditures abroad continued to be significant, primarily due to development of the Husab mine in Namibia.

37. The Salamanca uranium project in Spain is undergoing licensing, with several legal procedures completed in accordance with national regulations. The construction and the commissioning of the installation will require authorization by the government, subject to a report by the country's nuclear safety regulator.

38. In early 2017, Brazilian Nuclear Industries (INB) started work on its Engenho mine in Brazil's Bahia state, saying it expected to have produced 73 tU of concentrate within the year, with potential annual production of 280−300 tU of concentrate. Feasibility and regulatory work is ongoing for an underground extension or, alternatively, a second open pit at the existing Caetité mine.

39. Many uranium projects remained on hold or under low spending. Some projects that had been opened or were in advanced stages of construction remained on care and maintenance. A major announcement in November 2017 was the suspension of production from the McArthur River and Key Lake operations in Canada, for an expected period of 10 months.

Conversion and Enrichment

40. Current conversion and enrichment capacity is more than sufficient to meet demand, but the segmented nature of the market, with production centred on a few plants, presents a challenge.

41. Centrus Energy and the US Department of Energy's Oak Ridge National Laboratory signed a contract in October 2017 to continue their joint work to reduce costs and increase efficiency of the AC100 gas centrifuge enrichment technology.

42. Having passed the necessary tests and holding out the promise of significant energy savings, the advanced 'generation 9+' gas centrifuges will be introduced at the Russian Federation's Urals Electrochemical Combine in Novouralsk, Sverdlovsk Region, from 2018 onwards.

Fuel Fabrication

43. Under a contract that entered into force in January 2017, Rosatom subsidiary TVEL will produce and supply fuel assemblies in 2017 and 2018 for the China Experimental Fast Reactor, constructed by

its Russian partners. In September 2017, TVEL signed a contract with HAEK CJSC to supply nuclear fuel to the 440 MW Armenian-2 reactor for the next reload, as well as reserve fuel for two years.

44. In January 2017, CNNC subsidiary Baotou Nuclear Fuel Company received approval to produce Westinghouse Electric's AP1000 nuclear fuel rods. This enables CNNC to complete its fuel rod production line and to manufacture AP1000 fuel assemblies.

45. Marking a transition from test production line to industrial operation, mass production of fuel elements for high temperature gas cooled reactors (HTGR) began at China North Nuclear Fuel, in Baotou, in July 2017. Some 200 000 spherical fuel elements have already been produced at the facility, which has a capacity of 300 000 spherical fuel elements a year for the demonstration HTGR reactor under construction at Shidaowan in the Shandong Province.

46. Japan's NRA, in April 2017, permitted the amendment of permit for fuel fabrication at Global Nuclear Fuel – Japan's (GNF-J) fuel fabrication plant in Yokosuka, Kanagawa Prefecture, which is one of the key steps to conform to the new regulatory requirements introduced after the Fukushima Daiichi NPS accident. GNF-J is part of the GE-led Global Nuclear Fuel joint venture with Hitachi and Toshiba, for designing and manufacturing boiling water reactor fuel.

47. A shipment of 16 mixed oxide (MOX) nuclear fuel assemblies arrived at Japan's Takahama NPP in September 2017 from France, to be used in Unit 4 in 2018. AREVA[2] has been awarded a contract by Nuclear Fuel Industries to fabricate 32 MOX fuel assemblies for Kansai Electric Company's Takahama 3 and 4 units.

48. Canada's Cameco signed a ten-year extension agreement in May 2017 to continue supplying nuclear fuel to Bruce NPP.

49. In June 2017, Westinghouse Electric Company launched an accident tolerant fuel, EnCoreTM, hoping to manufacture lead test rods as early as in 2018. The company suggests the EnCore fuel will offer design-basis-altering safety and greater uranium efficiency, thus helping utilities save money.

50. In August 2017, Westinghouse Electric extended its contract with US power company PSE&G in New Jersey to provide fuel for both units of the Salem NPP.

51. AREVA and US-based nuclear fuel developer Lightbridge Corporation agreed in September 2017 on a 50–50 joint venture to be launched in early 2018, for manufacturing and commercializing a new line of advanced metallic NPP fuel. Lightbridge has developed the fuel, which can be used in existing and new plants under construction to improve operating efficiency and safety. In October 2017, Lightbridge signed orders with the Institute for Energy Technology (IFE), operator of Norway's Halden research reactor, for the design and manufacture of a second irradiation rig for testing of its fuels, a milestone in bringing its fuel technology to the market.

52. In February 2017, AREVA advanced to the second phase of the US Department of Energy's Enhanced Accident Tolerant Fuel, to enhance efficiency and reliability through chromia-doped pellets and chromium-coated cladding.

53. The Russian Federation continued to test two new fuel types — regenerated mixture (REMIX) fuel for light water reactors (LWRs) and uranium–plutonium mixed nitride fuel for fast reactors.

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[2] After restructuring of the French nuclear industry, AREVA was split into Orano (nuclear fuel operations) and Framatome (nuclear reactor operations) in January 2018.

A.3.2. Assurance of Supply

54. 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 (UMP) site in Ust-Kamenogorsk. Transit agreements with the Russian Federation and China have been signed, and negotiations of transport contracts with the authorized organizations from these two countries and Kazakhstan are advancing.

55. The Plan of Specific Activities is nearing completion, having addressed issues including those related to site safety and security. Construction of the IAEA LEU Storage Facility in Kazakhstan was completed in the summer of 2017. An Agency mission in August 2017 confirmed that the IAEA LEU Storage Facility had been built, commissioned and prepared for operation in accordance with the Agency's safety standards and security guidance documents, and that adequate measures had been implemented to assure the protection of workers, the public and the environment throughout its operation. The facility was inaugurated on 29 August 2017.

56. Progress has also been made in finalizing a Cylinder Management Programme that will ensure long term safety and security of cylinders in situ and in subsequent transport. A pilot test in April 2017 simulated the tests for cylinder recertification in accordance with the forthcoming relevant ISO standard, the results of which will inform the final Cylinder Management Programme. The request for proposal for LEU acquisition was issued in November 2017.

57. 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 management

58. To date, around 400 000 tonnes of heavy metal (t HM) have been discharged from NPPs. Currently about 25% of discharged fuel is being reprocessed, which is expected to rise to 30% by 2020. There are 151 away-from-reactor (AFR) dry spent fuel storage facilities in 27 countries.

59. Two countries signed contracts in 2017 for new AFR dry storage facilities: Slovenia at Krško NPP and Brazil for the storage of Angra-1 and 2 spent fuel. Krško is being designed to higher seismic and severe flooding requirements in accordance with post-Fukushima safety guidance.

60. he dry storage facility at Sizewell B in the UK, designed for 100 years of storage, received its first loaded fuel casks in 2017.

61. In Hungary, the Paks modular vault dry storage facility, with a previous capacity of 9308 fuel assemblies in 20 vaults, was expanded in 2017 with the addition of another four vaults.

62. The interim ISF-2 storage at Chernobyl NPP in Ukraine, which comprises a fuel cutting/packaging facility and spent fuel storage modules, is currently undergoing commissioning tests for RMBK fuel cutting operations. Regulatory permission to construct a new centralized dry storage facility for power reactor fuels in the Chernobyl Exclusion Zone was given in 2017, with start of operations planned in 2019.

63. During 2017 a number of industry innovations were reported. These include laser peening of welded dry storage canisters to mitigate the potential for stress corrosion cracking and the development of compact dry storage modules, which facilitate inspection of stored canisters.

64. As for spent fuel reprocessing and recycling, France increased the range of LWR used fuels to be treated at La Hague. The Russian Federation also continued to increase the range of fuels that can be reprocessed at the RT-1 plant of Mayak Chemical Combine at Ozersk. In this regard, the RT-1 plant was upgraded in 2017 to enable it to reprocess 20 t of VVER-1000 fuel.

65. The UK Nuclear Decommissioning Authority said in March 2017 that the Thorp Reprocessing Plant will cease operation around November 2018. Since 1994 around 9500 t of oxide fuel has been reprocessed at the plant.

66. In August 2017, the Indira Gandhi Centre for Atomic Research in India contracted Hindustan Construction Co to build the Fast Reactor Fuel Cycle Facility at Kalpakkam over the next 4 years. A multifunctional radiochemical research facility is currently under construction at the Research Institute of Atomic Reactors (RIAR) in the Russian Federation. Rosatom announced in May that this facility would be included under the umbrella of the International Research Centre (IRC) for testing technologies to close the fast reactor fuel cycle.

67. In August 2017, the first load of spent fuel from the Russian Federation's Northern Fleet storage facility at Andreeva Bay arrived by train for processing at the Mayak plant (a distance of 3000 kilometres). An estimated 50 train loads are planned to bring all 22 000 spent nuclear submarine fuel elements to Mayak, where processing is estimated to take 5 to 10 years.

A.3.4. Decommissioning, Environmental Remediation and Radioactive Waste Management

Decommissioning of Nuclear Facilities

68. Across the world, 164 power reactors have been shut down or are undergoing decommissioning. Of those, 17 reactors have been fully decommissioned, while several more are approaching the final stages of decommissioning. More than 150 fuel cycle facilities have been permanently shut down or are undergoing decommissioning and around 125 have been decommissioned. Over 180 research reactors have been shut down or are undergoing decommissioning and over 300 research reactors and critical assemblies have been fully decommissioned.

69. Research and development (R&D) work, mainly in countries with extensive nuclear power programmes, such as Belgium, France, Japan, the Republic of Korea, the Russian Federation, Spain, the United Kingdom and the USA, are delivering continuous improvement. In April 2017, the Japan Atomic Energy Agency opened the new Collaborative Laboratories for Advanced Decommissioning Science (CLADS) research centre in Tomioka, Fukushima Prefecture. The Tomioka International Collaborative Research Building will be the central CLADS facility for national and international institutions to work on R&D. In 2017, France's AREVA completed the dismantling of a fission products evaporator of a reprocessing plant by using laser technology.

70. Japan's Mid and Long-Term Roadmap and the Technical Strategic Plan for decommissioning the Fukushima Daiichi NPP were revised in 2017. Contaminated water generated by groundwater flowing into reactor buildings and mixing with the stagnant water used to cool fuel debris continues to be a major issue and is treated using a nuclide removal system. Freezing pipes have been installed for the landside impermeable walls to block groundwater since 2016, and freezing of the final section of the wall started in August 2017.

71. Notable progress on NPP decommissioning projects, supported by the European Bank for Reconstruction and Development, is being made in Bulgaria, Lithuania, Slovakia (Figure A-6) and Ukraine.

FIG. A-6. Demolition of V1 Bohunice NPP cooling towers, Slovakia, October 2017. (Photo: JAVYS).

Remediation

72. Progress in off-site decontamination was regularly reported by Japan. At the end of March 2017, the decontamination work had been completed for whole areas of the Special Decontamination Area, within a 20 km radius of the Fukushima Daiichi NPP, and also where the additional annual effective dose rate was anticipated to exceed 20 mSv in the first year after the accident. Regarding the Intensive Contamination Survey Area, where the air dose rate was measured over 0.23 uSv/h (equivalent to over 1 mSv/y of additional dose under certain conditions), the decontamination work had been completed in 89 municipalities and will be completed in the remaining 3 municipalities by the end of March 2018.

Management of Disused Sealed Radioactive Sources

73. End-of-life management options for disused sealed radioactive sources (DSRSs) were further supported in several Member States. Ghana and Malaysia made progress with borehole disposal projects, while several other countries expressed interest in possible implementation of borehole disposal. Developing and maintaining an inventory remains a priority in several Member States.

74. High activity source removal projects were initiated in 2017, with donor support, for Albania, Bolivia, Ecuador, Lebanon, the former Yugoslav Republic of Macedonia, Paraguay, Peru, Tunisia and Uruguay with projected completion in 2018. One high activity DSRS was removed from a hospital in Liberia and placed into safe and secure storage.

75. Operations for conditioning of Category 3–5 DSRSs were completed in several Member States, including Ghana, Honduras and Malaysia. Waste operators and regulatory personnel were trained during these missions and have increased their capacity for safely managing the DSRSs.

76. Significant progress was made in integrating a mobile hot cell into the borehole disposal system, which will minimize the handling of high activity sources and eliminate unnecessary transport. A demonstration of this integration was given in South Africa in September 2017. In addition, progress continued in assembling a mobile tool kit to support conditioning operations for Category 3–5 DSRSs. Training for Member States in its use is expected in early 2018.

77. Several Member States participated in the initial design and assessment process for Qualified Technical Centres, an Agency initiative for assistance in managing DSRSs, launched in 2017.

Radioactive Waste Predisposal

78. Sellafield Ltd announced in February 2017 that the first 500-litre drum of radioactive sludge (consisting of algae, corrosion products and wind-blown material) from Sellafield's Pile Fuel Storage Pond was cemented at the site's encapsulation plant and the capped waste form is ready for long-term disposal. Sellafield Ltd indicated that the sludge removal project is being delivered ten years ahead of schedule and for half the predicted £200 million ($249 million) cost.

79. A unique super compactor capable of exerting 1800 tonnes of pressure for compressing 200-litre waste filled drums has been in operation for more than 100 000 hours at the US Department of Energy's Idaho site. It has compacted more than 238 000 drums of waste debris during the past 14 years, saving an estimated 6000 truck shipments that would have been needed to take nearly 43 000 cubic metres of waste to the Waste Isolation Pilot Plant (WIPP).

80. Fuel element debris, totalling 65 tonnes, at the Bradwell nuclear power station in the United Kingdom was successfully removed by Magnox Ltd and subsidiaries, using innovative processing techniques. Having been re-classified, the solid waste was disposed of at the low level waste (LLW) repository.

81. The first of two 300-tonne smelters was successfully installed in the Low-Activity Waste Treatment Facility at Hanford, in the USA. The Pacific Northwest National Laboratory developed a mathematical high level waste (HLW) glass formulation algorithm for this smelter in order to achieve the optimal waste and additive mixture for each HLW batch to be vitrified.

82. Researchers at Bhabha Atomic Research Centre (BARC) announced the manufacturing of caesium-137 vitrified 'pencils' extracted from radioactive waste. This sealed source with a half-life of 30 years could replace the cobalt-60 sources (which have a shorter half-life of 5.3 years) currently used for food irradiation, brachytherapy and sterilization of medical equipment.

83. The establishment of a treatment facility capable of dealing with 10 000 cubic metres of solid radioactive waste at Sayda Bay in Northern Russia has cleared the State environmental impact assessment and is to condition and manage this type of radioactive waste under the auspices of SevRAO, Northwest Russia's nuclear waste handler.

84. Switzerland's Federal Nuclear Safety Inspectorate approved the construction of the interim storage facility for low and intermediate level nuclear waste (LILW) at the Paul Scherrer Institute. The planned 'Stapelplatz Ost' building in Würenlingen will store waste from radioisotope applications in medicine and industry until a deep geological repository becomes available.

85. Researchers from China General Nuclear Power Corporation and Tsinghua University jointly developed an electron beam irradiation system to treat industrial wastewater. By irradiating the effluent using electron beams, more than 70 complex chemicals can be reduced into smaller molecules that can be treated and removed using normal biological processes.

Radioactive Waste Disposal

86. Disposal facilities for all radioactive waste categories, except high level waste and/or spent fuel declared as waste, are operational worldwide. These include trench disposal for very low level waste (e.g. France, Spain, Sweden, the USA) or for low level waste (LLW) in arid areas (e.g. South Africa, the USA); near surface engineered facilities for LLW (e.g. China, the Czech Republic, France, Hungary, India, Japan, Poland, Slovakia, Spain, the United Kingdom); and engineered facilities for low and intermediate level waste (LILW) sited in geological formations at a range of depths (e.g. the Czech Republic, Finland, Germany, Hungary, the Republic of Korea, Norway, the USA). Disposal facilities for LILW, such as in Belgium, Bulgaria, Canada, Germany, the Islamic Republic of Iran, Lithuania, Romania and Slovenia are at different stages of licensing or construction. Disposal options considered for naturally occurring radioactive material waste vary according to national regulations.

87. Canada's spent fuel disposal programme progressed towards siting a deep geological disposal facility in 2017, with continued participation in the site selection process of seven of the original 22 interested communities. With regard to the licence application for the LILW geological disposal facility in Kincardine, the Minister of Environment and Climate Change requested additional information on

the environmental impact statement submitted by Ontario Power Generation for further review by the Canadian Environmental Assessment Agency.

88. The Chinese geological disposal programme for the future vitrified high level waste inventory continues, with site investigations in both crystalline and sedimentary formations. It is currently considering construction plans for an underground research facility in the Beishan area crystalline rock formation, and further surface-based site surveys for an inner Mongolia sedimentary formation.

89. Constructing the world's first spent nuclear fuel deep geological disposal facility in Olkiluoto, Finland's Posiva examined technological and operational developments, such as full scale in situ systems tests and further construction and operating tests, to prepare cold and hot commissioning, with a view to obtaining the operating licence.

90. The French radioactive waste management organization Andra continued to implement technological developments, with in situ demonstrators and scientific experiments, to ensure that the licence application for its planned deep geological disposal facility will have a robust scientific and technical basis.

91. In March 2017, the German Parliament amended the law on siting geological disposal, following recommendations by its Commission on HLW Storage, which include basing the siting decisions on safety relevant criteria and providing for comprehensive stakeholder engagement. Also in 2017, under the law on nuclear back-end liabilities, NPP operators transferred €24.1 billion into the national fund for financing nuclear waste disposal, and thus transferred the entire responsibility of storage and disposal to the State. Operators remain responsible for decommissioning, waste treatment and conditioning activities.

92. In July 2017, Japan's Ministry of Economy, Trade and Industry published a nationwide map of scientific features relevant for geological disposal as the first step toward final disposal.

93. The Russian Federation's National Operator for Radioactive Waste Management (NO RAO) started operating its first near surface LLW disposal facility in Novouralsk, in the Sverdlovsk region. It is the first of several such facilities planned to address the national legacy of radioactive waste.

94. Environmental licensing of SKB's construction licence application for geological disposal of spent fuel was concluded in October in Sweden's Land and Environment Court, which will submit its conclusions to the Government. The Oskarshamn Municipality, the Swedish Radiation Safety Authority and other authorities reiterated that they are in favour of granting permissibility under the Environmental Code, while the Östhammar Municipality will give a final answer after a referendum.

95. The Swiss radioactive waste management organization, Nagra, submitted applications to further investigate the geological and hydrogeological properties of the underground rock formations in the siting region Nördlich Lägern of the geological repository programme.

96. In the USA, post-accident recovery at the WIPP geological disposal facility for transuranic LILW has progressed sufficiently to allow operations to start again in April 2017, albeit at a reduced emplacement rate compared to before the 2014 accident.

B. Advanced Fission and Fusion

B.1. Advanced Fission

97. Nuclear power is a mature, tested technology that helps to improve energy security, reduces the impact of volatile fossil fuel prices, makes economies more competitive and emits significantly lower greenhouse gases and other pollutants than fossil fuels. As in any other industrial sector, R&D and continuous innovation of technologies[3] are essential to keep nuclear power competitive and an attractive option even in changing business environment, including for newcomer countries.

B.1.1. Water Cooled Reactors

98. Water cooled reactors (WCRs) play a key role in the nuclear industry, with over 17 000 reactor-years of commercial operation. Over 95% of all operating civilian power reactors in the world and 56 of the 58 under construction are cooled with light or heavy water. In 2017, three new WCRs were connected to the grid, in China and Pakistan, and construction started on two units, in India and the Republic of Korea (Fig. B-1). Most newcomers choose advanced WCRs as their first reactors, as is the case in Belarus and the United Arab Emirates. The Agency's sixth International Conference on Topical Issues in Nuclear Installation Safety, held in June 2017, focused on demonstration of the safety of advanced water cooled NPPs, including small and medium sized or modular reactors.

99. Most advanced WCRs have increased power output. Those of recent construction have an output of 1000–1700 MW per unit, and further increases are planned in evolutionary designs. There is a clear trend towards multi-unit sites with a single or multiple types of reactor, favouring economies of scale. Advanced versions of existing WCRs are being considered, studied and built in several countries for the gradual deployment of more efficient, partially or fully closed fuel cycles. India is making progress in its three-phase strategy towards thorium based nuclear energy, with heavy water reactors (HWRs), fast reactors and its advanced HWR with a Th/^{233}U fuel cycle. China has fully fuelled one operating CANDU reactor with a natural uranium equivalent blend of used light water reactor (LWR) fuel and depleted uranium tailings.

100. Several Member States are conducting R&D on supercritical water cooled reactors (SCWRs). The conceptual design of the Canadian SCWR, a heavy water moderated pressure tube reactor concept, and the Chinese CSR1000 has been completed. The concept of a European high performance LWR was created in Europe, and an in-pile fuel qualification test facility was planned, designed and analysed in collaboration with China. In the Russian Federation, conceptual studies on an innovative water cooled, water moderated power reactor (VVER) with supercritical parameters of water coolant are under way, including the possibility of a fast-spectrum core.

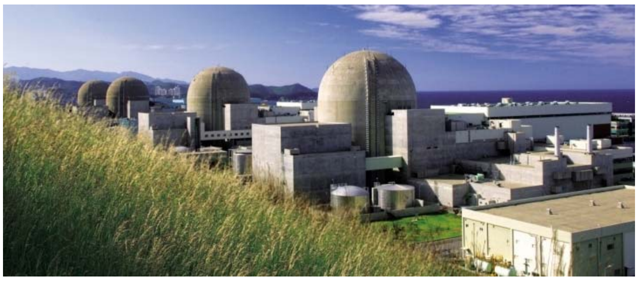

FIG. B-1. Hanul (formerly Ulchin) NPP, Republic of Korea, has six units in operation, with two more under construction. (Photo: KHNP)

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[3] See the Agency's Advanced Reactors Information System (ARIS) for more information: https://aris.iaea.org.

B.1.2. Fast Neutron Systems

101. Significant fast reactor programmes have been pursued worldwide since 1960. The third International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development, held in June 2017 in Yekaterinburg, Russian Federation, concluded that a closed nuclear fuel cycle based on fast reactors can provide efficient, safe, sustainable, clean energy for many generations, especially in terms of resource preservation and management of high level and long lived nuclear wastes. Several innovative sodium cooled fast reactors (SFRs), lead and lead–bismuth eutectic cooled fast reactors (LFRs) and gas cooled fast reactors (GFRs) are under development at national and international levels. The molten salt fast reactor (MSR) is also being developed as a long term option.

102. The most mature fast reactor technology, the SFR, has more than 420 reactor-years of experience acquired through the design, construction and operation of experimental, prototype, demonstration and commercial units in several countries, including China, France, Germany, India, Japan, the Russian Federation, the United Kingdom and the USA.

103. The Russian SFR, BN-800, went into commercial operation in October 2016 (Figure B-2). The multipurpose research SFR, MBIR, which will replace the experimental BOR-60 reactor in 2020, is under construction; the reactor vessel was produced in 2017. With regard to heavy liquid metal technology, the lead cooled BREST-OD-300 is under licensing procedure.

FIG. B-2. The BN-800 sodium cooled fast reactor started commercial operation on 31 October 2016. (Photos: Rosenergoatom)

104. In India, construction of the 500 MW(e) prototype fast breeder reactor is complete, with first criticality expected in 2018. Two more fast breeder reactors are planned at the same site.

105. China's lead based CLEAR-I, which is under engineering design, was selected in 2017 as the reference for accelerator driven system (ADS) and fast reactor development. The innovative CFR-600 is in engineering design phase, with plans to start operation in 2025.

106. In December 2016, Japan's Government decided to decommission the SFR prototype Monju, which was in long term shutdown. Development of the innovative sodium cooled reactor JSFR will continue, as fast reactor technology is considered vital for the future energy mix of Japan.

107. In Europe, the French Government authorized the basic design phase of the industrial SFR prototype ASTRID to proceed until the end of 2019. In Belgium, the construction of MYRRHA, a lead–bismuth cooled reactor that can operate in subcritical and critical modes as an ADS, is under consideration; the target is to make its first R&D facility available by the end of 2024. The Swedish Advanced Lead Reactor (SEALER) is undergoing pre-licensing with the Canadian Nuclear Safety Commission. The target is to start construction of this 3-10 MW(e) "battery" reactor, designed for commercial electricity production in Arctic communities and mining operations, by the end of 2021 and to commission the demonstration unit in 2025. Other concepts under development are ALFRED, the European demonstration of a Generation IV LFR, and ALLEGRO, an experimental GFR.

108. In the USA, TerraPower has completed the core conceptual design of the “breed-and-burn” travelling wave reactor and is developing an MSR. Westinghouse is developing an innovative lead cooled 450 MW(e) small modular reactor.

B.1.3. Gas Cooled Reactors

109. The United Kingdom continues commercial operation of 14 advanced gas cooled reactors and is conducting life extension studies. Many Member States are developing small modular HTGRs with inherent safety characteristics that eliminate the need for most active engineered safety systems. With coated particle fuel, helium as coolant and operating at high temperatures (≥ 700 ºC), an HTGR would increase efficiency and serve the process heat market.

110. In China, construction of the High Temperature Reactor–Pebble-Bed Module (HTR–PM) is complete. The 200 MW(e) industrial demonstration power plant, with two 250 MW(th) reactors, is expected to be in operation in 2018. The reactor pressure vessels have been installed, and the core internals and graphite spheres (part of the startup core) have been loaded into one of the units. A 600 MW(e) commercial plant is being designed, with feasibility studies for five possible sites under way. The commercial scale pebble fuel fabrication plant in Baotou started production in 2016.

111. Saudi Arabia identified future deployment of HTGR in its National Atomic Energy Project. A memorandum of understanding has been signed with China to establish a long term strategic partnership to localize and own the technology. A joint feasibility study that includes industrial process heat applications in the petrochemical industry was completed in 2017.

112. In September 2017, Poland’s Minister of Energy accepted the report of an advisory committee that called for deployment of HTGRs, which would also replace over 6500 MW of industrial heat currently provided by hydrocarbon sources. The plan includes hosting the ~10 MW(th) European High Temperature Experimental Reactor to facilitate new technology and human resource development.

113. Having received an initial site licence for its 10 MW(th) pebble bed experimental power reactor, Indonesia’s National Nuclear Energy Agency is seeking to secure construction funding.

114. In Japan, the results of the regulatory review to restart the 30 MW(th) High Temperature Engineering Test Reactor (HTTR) are awaited before further safety and technology demonstration tests can be conducted.

115. Activities in the USA focus on fuel qualification of tri-structural isotropic coated particle fuel for future deployment. Progress has been made in establishing a new licensing framework for advanced reactors, specifically HTGRs.

116. HTGR related activities continue in the European Commission with the GEMINI+ programme, in South Africa with R&D on a new advanced high temperature reactor (HTR) pebble bed concept and in the Republic of Korea and the Russian Federation to develop and maintain key technologies. Three Agency coordinated research projects address analysis uncertainty, development of safety design criteria and the application of HTGR heat for more sustainable, clean mineral extraction.

B.1.4. Small and Medium Sized or Modular Reactors

117. Many Member States are increasingly interested in small and medium sized or modular reactors (SMRs). Components and systems of these newer generation reactors with up to 300 MW(e) power can be fabricated in a factory and installed at sites as modules. Envisioned for niche electricity or energy markets where large reactors would not be viable, SMRs can meet the need for flexible power generation for a wide range of users and applications, including replacing ageing fossil power plants, providing energy for countries with small electricity grids, remote and off grid areas, and enabling hybrid nuclear

and renewable energy systems. They are also better suited for partial or dedicated use in non-electrical applications, such as heat for industrial processes, hydrogen production and seawater desalination. Although SMRs promise to have enhanced safety features and to be more affordable, these characteristics are yet to be fully demonstrated.

118. Over 50 SMR designs of all major reactor types are under development, of which three are in advanced construction stages: Argentina's 27 MW(e) CAREM-25 (a prototype of the 150–300 MW(e) integral PWR CAREM) (Fig. B-3), planned for start-up commissioning in 2019; the HTR-PM in China, planned to be operational in 2018; and a barge mounted floating NPP in the Russian Federation, with two 35 MW(e) KLT-40S PWR modules, planned for start-up commissioning in 2018.

FIG. B-3. CAREM-25 under construction (left); final plant layout (right). (Photos: CNEA, Argentina)

119. The Canadian Nuclear Safety Commission has already received ten applications for pre-licensing vendor design reviews, and the Canadian Nuclear Laboratories have stated their interest in becoming hubs for demonstration SMRs. A long term strategy report published in 2017 includes the goal of siting a new SMR on Chalk River by 2026.

120. Construction of the first industrial demonstration plant with two China National Nuclear Corporation ACP100 modules is planned to start in 2018 at Changjiang NPP site in Hainan. The China General Nuclear Power Group has started manufacturing systems and components for ACPR50S, an offshore floating reactor; connection to the grid is expected in 2022. The Shanghai Nuclear Engineering Research and Design Institute has completed the conceptual design stage for its CAP150 and CAP200.

121. In France, a consortium led by EDF, which includes the French Alternative Energies and Atomic Energy Commission (CEA), Naval Group and TechnicAtome, is developing a land-based 150–170 MW(e) integral-PWR type SMR. The Naval Group also continued to develop Flexblue, a 160 MW(e) transportable, immersed PWR.

122. The King Abdullah City of Atomic and Renewable Energy (KACARE) has acquired design co-ownership of the 100 MW(e) SMART of the Korea Atomic Energy Research Institute (KAERI), after an agreement in 2015 on deployment of two units in Saudi Arabia. The Jordan Atomic Energy Commission is conducting a feasibility study for the construction of two SMART units for electricity production and water desalination, in partnership with KACARE and the KAERI.

123. The Russian Federation has developed the 50 MW(e) RITM-200, an integral reactor for nuclear icebreakers, which is expected to be commissioned in 2020. To approach the characteristics of innovative fast reactors, a multipurpose lead-bismuth eutectic cooled fast reactor with 100 MW(e) power, SVBR-100, has been developed. The technology has already been used in several Russian nuclear submarines. The design organization is working on a pilot plant, with serial production expected by 2030.

124. The Government of the United Kingdom launched a competition in March 2016 for further exploration of the potential of SMRs in studies such as techno-economic assessments and to give the industry an opportunity to engage with the Government on drivers and enablers for deployment. Rolls-

Royce plc is developing the UK SMR, a loop-type 450 MW(e) PWR with standardized transportable modules.

125. In March 2017, the US NRC accepted for docketing and review the design certification application of NuScale, a 12-module integral PWR, each with 50 MW(e) power. NuScale Power plans to start commercial operation of its first plant in Idaho by 2026 and has launched a plan for near term deployment in the United Kingdom. The US Department of Nuclear Energy's Gateway for Accelerated Innovation in Nuclear (GAIN) is providing support for the development of SMR-160, another integral PWR developed by Holtec International.

126. A new entry onto the market is the molten salt fuelled (and cooled) advanced reactor (MSR). Among the several potential benefits of MSRs are higher operating temperatures, which increase efficiency, low coolant pressure, a reduced volume and lifetime of high level waste, remarkable safety characteristics, elimination of challenges associated with high burn-up effects of solid fuel and flexible fuel cycles (uranium, plutonium, thorium). One of many conceptual designs is the integral MSR, IMSR400, being developed by Terrestrial Energy Canada, which has about 190 MW(e) power.

127. For expeditious deployment of SMRs, certain challenges need to be overcome. A robust regulatory framework should be available for regulatory reviews of institutional issues. Technical challenges include control room staffing and human factor engineering for multi-module SMR plants, determining the size of the emergency planning zone, developing new codes and standards and building a resilient supply chain. Furthermore, although SMRs require less upfront capital per unit, their electricity generating cost will probably be higher than that of large reactors. Their economic competitiveness must be weighed against that of alternatives and be pursued through economies of scale. Realistically, the first commercial SMR fleet could be expected to start between 2025 and 2030, with large fleet deployment subsequently. International collaboration and partnerships are key to advancing SMR development and deployment.

B.1.5. International Initiatives on Innovative Nuclear Energy Systems

128. Several international initiatives on innovative nuclear energy systems have been launched in the past few decades to help resolve issues including the growing energy demand, the availability of uranium fuel resources, recycling of spent nuclear fuel to reduce the future burden of geological repositories, improved thermal efficiency, enhanced safety by design and resistance to proliferation.

129. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), established at the Agency in 2000, brings together technology developers, suppliers and customers to consider international and national actions for achieving desired innovations in nuclear reactors and fuel cycles for long term sustainability of nuclear power. INPRO currently has 42 members – 41 IAEA Member States and the European Commission.

130. An updated INPRO manual on assessment of the sustainability of environmental stressors was published in 2016. Nuclear Energy System Assessments (NESAs), based on the INPRO methodology, are under way in Romania and Ukraine, and China, India and the Russian Federation are conducting limited scope assessments on their most recent SFR designs. In 2017, the INPRO Steering Committee endorsed the development of a new service for Member States based on nuclear energy system scenario modelling, analysis and roadmapping tools developed under INPRO during the past several years. The new service will complement the existing NESA service.

131. In 2017, Australia joined the Generation IV International Forum (GIF), a cooperative international endeavour for studying the feasibility and performance of next-generation nuclear reactors. The 14 GIF members engage in cooperative R&D on one or more of six nuclear energy systems: GFRs, very high temperature reactors, SCWRs, SFRs, LFRs and MSRs. Annual GIF–IAEA interface meetings

are held on methods for assessing areas of economics and proliferation resistance, which enable information exchange on ongoing projects.

132. In 2016, the GIF published a report entitled *Safety Design Guidelines on Safety Approach and Design Conditions for Generation IV Sodium-cooled Fast Reactor Systems*, to provide guidance to developers and vendors on fast reactor core reactivity and on loss of heat removal. This follows the GIF activity launched in 2011, in cooperation with the Agency, to develop safety design criteria for SFRs, which was published in 2013.

133. The European Union's Sustainable Nuclear Energy Technology Platform (SNETP) brings together over 100 European stakeholders from industry, research, academia, safety, governmental and non-governmental organizations to promote research, development and demonstration of advance fission technologies to achieve the European Strategic Energy Technology Plan. The European Sustainable Nuclear Industrial Initiative, launched in 2010 under SNETP, addresses the need for demonstration of Generation IV fast neutron reactor technology. In its Strategic Research and Innovation Agenda, SNETP prioritized the various next generation systems and proposed development of the following projects: the ASTRID SFR project as the reference solution, with the construction of a prototype in France around 2020; the ALFRED LFR, as a first alternative, with the construction of an experimental reactor to demonstrate the technology in another European country willing to host this programme, supported by MYRRHA in Belgium; and the ALLEGRO GFR as a second alternative, also requiring construction of technology demonstrator in a European country.

134. Among recent international initiatives for designing roadmaps to a carbon free energy future is the Nuclear Energy Agency's (NEA's) Nuclear Innovation 2050 (NI2050). The aim of NI2050, which involves a number of OECD countries as well as representatives from SNETP, GIF, WNA and the Agency, is to help set global priorities for nuclear fission R&D, foster their implementation and identify opportunities for enhanced cooperation.

B.1.6. Non-electric Applications of Nuclear Power

135. The use of nuclear energy for non-electric applications, also known as nuclear cogeneration, is gaining interest. Cogeneration can be used in seawater desalination, hydrogen production, district heating, tertiary oil recovery and other industrial applications and can also help to ensure energy security, sustainability and combat climate change. It could increase the overall thermal efficiency of an NPP by more than 30% by reusing waste heat and could decrease the environmental impacts of heating and transport by up to 35% if it penetrates those markets.

136. Recent studies show that cogeneration with waste heat can offset a significant part of the cost of nuclear power generation. For example, the waste heat rejected by HTGRs could be used in seawater desalination, which would result in major cost credits against the price of water produced by desalination in gas or oil-fired power plants.

137. With current advancements in the technology for seawater desalination, such as low temperature operating systems, waste heat recovery systems, efficient energy and process systems and innovative process optimization, nuclear desalination from NPPs will be a viable option in the future. An integrated hybrid thermal and membrane design is seen as optimal for using the reject heat discharged from condensers of NPPs or extracted as low quality process steam from late stages of a low pressure turbine and fed to a multiple effect distillation desalination system. This could reduce energy consumption, the volume of seawater intake and the cost of outfall. Several Member States, including China, Egypt, Jordan, Pakistan and Saudi Arabia, have expressed or renewed interest in nuclear desalination. Several reactor designs under development, such as SMART in the Republic of Korea, will use waste heat for seawater desalination.

138. With the progress made in HTR designs and in nuclear hydrogen production, especially in high temperature steam electrolysis, nuclear hydrogen production may play an increasing role in the future hydrogen economy and help to combat climate change. Current low temperature nuclear reactors could also produce hydrogen through advanced low temperature water electrolysis. The economics of this process could be improved by using the off-peak electricity generated.

139. Whether for district heating or other purposes, NPPs can provide adequate, cost effective process heat or steam with current technical options to transport large amounts of heat (~GW) over long distances (~100 km). The cost of the heat delivered to customers may be competitive whenever the heat recovered from an NPP exceeds a threshold value.

B.2. Fusion

140. Significant progress has been made in the ITER project, with more visible site construction and assembly (Fig. B-4). Major components continue to arrive, and others are being manufactured. Central team activities are design completion, technical integration and nuclear safety. In parallel, a wide ranging R&D programme being conducted by the parties involved in ITER is supporting finalization of plasma facing components, heating and current drive, diagnostics and control systems. After several revisions of the schedule, ITER and seven domestic agencies concluded that the first plasma will be produced by the end of 2025.

141. Another milestone in fusion energy was the first production of plasma at the optimized stellarator Wendelstein 7-X (W7-X), at the Max Planck Institute for Plasma Physics, Germany (Fig. B-4). The main objective of this machine is to demonstrate steady-state plasma operation at parameters relevant to fusion, thereby verifying that the stellarator is a viable fusion power plant concept. After completion of the main construction phase of W7-X and successful commissioning of the device, plasma operation was conducted on three days each week between December 2015 and March 2016, comprising 10 weeks of plasma operation. While the magnetic field coils and their support structure inside the cryostat were kept at a cryogenic temperature (100 K) throughout the campaign (in a magnetic field, the operational temperature of the W7-X coils is 4 K), the magnetic field was ramped up and down each day of plasma operation.

FIG. B-4. Left: ITER site in October 2017. (Photo: ITER IO). Right: Outside view of stellarator Wendelstein 7-X. (Photo: Max Planck Institute for Plasma Physics)

142. Several R&D programmes on fusion engineering, integration, power plant design, materials and safety continued. Substantial R&D is being done on a fusion neutron source in China, Europe and Japan. The aim of the engineering validation and engineering design activities of the International Fusion Materials Irradiation Facility (IFMIF), jointly by Europe and Japan, is to produce a detailed, complete, fully integrated engineering design and to validate continuous, stable operation of prototypes of each IFMIF subsystem. The performance of the lithium target facility, the low-beta half-wave resonators and other subsystems has been validated. Complete validation of the linear IFMIF prototype accelerator is planned for 2019.

143. The China Compact Fusion Neutron Sources, still under construction, is expected to achieve a fast neutron flux of up to 10^{14} $cm^{-2}s^{-1}$by the end of 2018.

144. The Agency is developing standards and guidelines for small specimen test techniques, which will be used, with fusion dedicated neutron sources, in materials selection and qualification procedures.

C. Accelerator and Research Reactor Applications

C.1. Accelerators

145. The most common applications of ion beam accelerators include environmental studies, biomedical applications, cultural heritage characterization and provenancing, materials science and radiocarbon dating.[4]

Super-resolution nuclear microscopy of whole cells

146. Ion beam accelerators with ion energies of a few megaelectronvolts combined with a sophisticated focusing system can provide beams a few tens of nanometres in diameter. This offers an opportunity for imaging whole biological cells at resolutions well below the optical diffraction limit.

147. Recent developments in focusing systems and light detection instruments have resulted in progress in bioimaging with nuclear microprobes. Figure C-1 shows combined fluorescence and structural imaging of a whole HeLa cell cultured in a medium containing fluorescent nanodiamonds. The spot size used for imaging was 30 nm, which is one of the smallest beam sizes ever achieved for 1.6 MeV ions. These developments contribute to understanding the effects of radiation on single live cells and to developing new therapies and medicines.

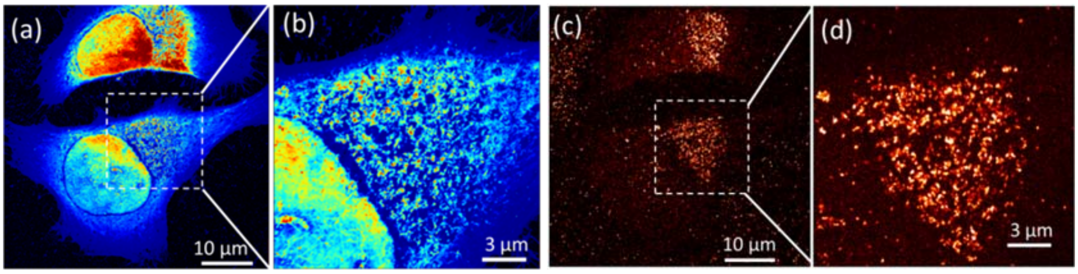

FIG. C-1. Uptake of nanodiamonds by HeLa cells. (a) and (b) Scanning transmission ion microscopy images showing differences in density. The cell nucleus can be clearly seen. (c) and (d) Ion beam induced fluorescence imaging showing the location of nanodiamonds (Photos: A/P Andrew Bettiol, Centre for Ion Beam Applications, National University of Singapore)

Age determination with ion beams

148. Use of ion beam techniques has also been extremely useful in crime investigation, food safety and health issues, cultural heritage artefacts and environmental samples. Determination of absolute age by radiocarbon dating is useful in identifying forgeries and is now a well-established tool in cultural heritage diagnostics (Fig. C-2). Radiocarbon dating is based on measurement of residual concentrations of ^{14}C in a sample by accelerator mass spectrometry. The Agency launched a coordinated research project in 2017 to raise awareness and bridge the gap between practitioners of nuclear analytical techniques and forensic science communities.

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[4] See IAEA Accelerator Knowledge Portal for more information: https://nucleus.iaea.org/sites/accelerators.

FIG. C-2. Sampling of the famous bronze Capitoline wolf at the Centre for Dating and Diagnostics, University of Salento, Lecce, Italy (left). The bronze statue had been considered to be Etruscan work from around 500 BC. Samples of the original casting cores were taken, organic residues were selected by optical microscopy, and radiocarbon dating at the accelerator end station (right) gave the final answer: the statue was made some time between 1100–1200 AD and is thus about 16 centuries younger than was thought.
(Credits: G. Quarta, L. Calcagnile, University of Salento).

SESAME delivers the first synchrotron light to users

149. The Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) emitted its “first light” in January 2017 and was inaugurated in May (Fig. C-3). The new research facility in Jordan has a 2.5 GeV third generation synchrotron light source, the first of its kind in the Middle East, which can emit high-brilliance radiation over wavelengths from infrared to hard X-rays for a variety of scientific applications, including biology, advanced materials, cultural heritage and condensed matter physics. With UNESCO as the lead international organization, SESAME has benefitted from support from many IAEA Member States, the European Union and CERN.

FIG. C-3. The inner storage ring of SESAME, with deflection and focusing magnets through which the electron beams circulate as they are accelerated (left). The first beam delivered, as visualized by the data acquisition system in the control room of SESAME. (Photos: IAEA)

C.2. Research Reactors

150. TAs of 31 December, 797 civilian research reactors have been built in 67 countries,[5] of which 254 are in operation in 55 countries[6]. The Russian Federation has the largest number of operating research reactors (59), followed by the USA (50), China (17) and Japan (9). Worldwide, 57 research reactors operate at a power level of 5 MW or higher and thus offer high neutron fluxes that support high capacity products and services.

151. 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 sector and services for cultural heritage and environmental studies (Table

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[5] Source: The Agency’s *Research Reactor Database* (http://nucleus.iaea.org/RRDB/).

[6] Plus Taiwan, China.

C-1). 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 operate sustainably. The Agency encourages research reactor operators to develop or update strategic plans for the use of their facilities. In the past three years, 41 facilities submitted their strategic plans to the Agency for further advice.

152. Half the 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 management and life management programmes will be vital so that they can fulfil their missions cost effectively. Several of the 122 research reactors that are in permanent shutdown status in 27 Member States are expected to start preparing for decommissioning in the near future.

153. New research reactors are being constructed in Argentina, France, India, 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 Argus-FTI reactor), Thailand, the USA, 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. The 5 MW multipurpose Jordan Research and Training Reactor at the Jordan University of Science and Technology was commissioned and received its operating licence in November 2017. Having met the post-Fukushima safety requirements, the zero power KUCA and the 5 MW KUR research reactors at Kyoto University, as well as the zero power UTR research reactor at Kindai University, were put back into operation in 2017. The 30 MW multipurpose HANARO research reactor in the Republic of Korea resumed operation in December after being shut down for more than three years for retrofitting of the reactor building.

Table C-1. Common applications of research reactors around the world. [a]

Type of application	Number of research reactors involved [b]	Number of Member States hosting such facilities
Teaching and training	157	53
Neutron activation analysis	114	52
Radioisotope production	83	43
Neutron radiography	68	38
Material and fuel irradiation	62	26
Neutron scattering	44	29
Geochronology	25	22
Transmutation (silicon doping)	23	16
Transmutation (gemstones)	18	11
Neutron therapy, mainly R&D	14	11
Innovative nuclear energy research	15	10
Other[c]	118	37

[a] The Agency publication *Applications of Research Reactors* (IAEA Nuclear Energy Series No. NP-T-5.3, 2014) describes these applications in more detail.

[b] Of 238 research reactors considered (217 operational, 21 temporarily shut down in November 2017).

[c] Such as calibration and testing of instrumentation, shielding experiments, nuclear data measurements, public visits, seminars.

154. 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 2017, the Agency consolidated and expanded its four instruments and tools: the Internet Reactor Laboratory, a distance training tool mainly for academic education (broadcasting sessions continued in 2017 for the African, European and Latin America and Caribbean regions); the Research Reactor Regional Schools (RRRS), for basic training, and the Eastern Europe Research Reactor Initiative (EERRI) for advanced hands-on training, mainly for young professionals (in 2017, a RRRS was organized jointly by Thailand and Viet Nam, and the 13th EERRI Training Course took place in Austria, Czech Republic and Hungary); and the IAEA-designated International Centre based on Research Reactor (ICERR) scheme for specific, advanced training for young and senior professionals (SCK•CEN in Belgium and the US Department of Energy – Idaho National Laboratory and Oak Ridge National Laboratory – were designated in 2017).

155. Continued safe, reliable, economic management and storage of research reactor spent nuclear fuel (SNF) represent a challenge for several Member States, as does identification of viable back-end options, which must comply with non-proliferation, national policy, economics and environmental requirements and constraints as well as with technical issues. Many countries with one or more research reactors and no or a small nuclear power programme face the problem of final disposal of relatively small amounts of SNF; they may be obliged to take a decision on the future of their research reactors considering the limited duration of the international research reactor SNF take-back programmes. A collective effort coordinated by the Agency is under way to develop decision making models to help Member States select the most feasible option for their scenario.

156. To date, 97 research reactors and two medical isotope production facilities have been converted from use of high enriched uranium (HEU) to LEU or confirmed as being shut down. In 2017, the miniature neutron source reactor (MNSR) in Ghana was converted from HEU to LEU fuel, and the irradiated HEU fuel was returned to China. Support is being provided for the conversion of the Nigerian MNSR. Development and qualification of high density LEU fuels (e.g. uranium–molybdenum) are necessary to convert high flux, high performance research reactors; despite substantial progress, further work in irradiation testing, post-irradiation examination and manufacturing techniques is necessary to make them commercially available.

157. By the end of 2017, the programme for the return of US origin HEU fuel had completed the removal of approximately 1300 kg of fresh and spent HEU research reactor fuel, and the Russian origin return programme had completed the removal of approximately 2250 kg.

158. In France, AREVA increased the range of research reactor used fuels to be treated, such as silicide fuel, which was reprocessed for the first time in 2017.

159. Brief outages at some global molybdenum-99 target irradiation facilities and processors in 2017 did not result in supply shortages significant enough to impact on patients, as efforts by supply chain management bodies and major international producers, as well as effective mitigation efforts by health practitioners, compensated for the fluctuations. The end of routine molybdenum-99 production at Canada’s National Research Universal research reactor in 2016 has had no negative effect on global supply. The conversion of molybdenum-99 production processes from HEU to LEU continues. In 2017, the Australian Nuclear Science and Technology Organisation completed constructing its new production facility. NTP Radioisotopes (South Africa) announced full conversion of its processes to use of LEU. Two other major producers, the Institute for Radioelements in Belgium and Curium (uniting IBA Molecular and Mallinckrodt Nuclear Medicine LLC) in the Netherlands, continue to progress in converting their production processes from HEU to LEU.

D. Food and Agriculture

D.1. Nuclear Emergency Preparedness in Food and Agriculture

D.1.1. Challenges in nuclear emergency response

160. Quickly identifying affected food production areas and preventing potentially contaminated products from reaching consumers are some of the challenges that would require overcoming during nuclear emergencies. However, traditional processing of radioactive contamination data impacts both response times and accuracy of response. Owing to the possible large scale of a nuclear emergency, multiple laboratories of different institutions could be involved, providing multifaceted information often obtained through a wide range of methodologies. Effective and efficient management of these large and often diverse data may determine the quality of response.

161. This can be achieved by using a robust Information Technology Decision Support System (IT-DSS) where all relevant information is collected and centralized, and real-time data processing targeted.

D.1.2. New developments in decision support systems for emergency response

162. Developments in IT-DSS tools and algorithms allow for improved real-time management of large volumes of data and integrated decision-making support. Use of mobile technologies in field and laboratory data collection reduces human error and achieves faster information processing.

163. The modern IT-DSS provides clear visual aid for improving response capabilities. Examples include the potential to graphically represent the collection phase (maps showcasing status of sample collection or analysis), the analysis/validation phase (maps showcasing radioactivity concentration/deposition) and the decision-making phase (dashboard assisting in suggesting food restriction sites). Food contamination maps can be made available immediately, so that all involved parties can make informed decisions. Provision of map legends with pre-set colour ranges can also be used to facilitate risk communication between stakeholders and citizens.

164. The ability to visually assess real-time data helps weigh cost and benefits of possible response scenarios. Threshold values and action levels, determined by each stakeholder in the scenario forecasting process, accommodate for varying levels of risk allowances in suggesting restrictions on agriculture and the movement of food. These decision-making support functions increase the capacity of stakeholders to focus on the most important matters at hand — ensuring food and consumer safety.

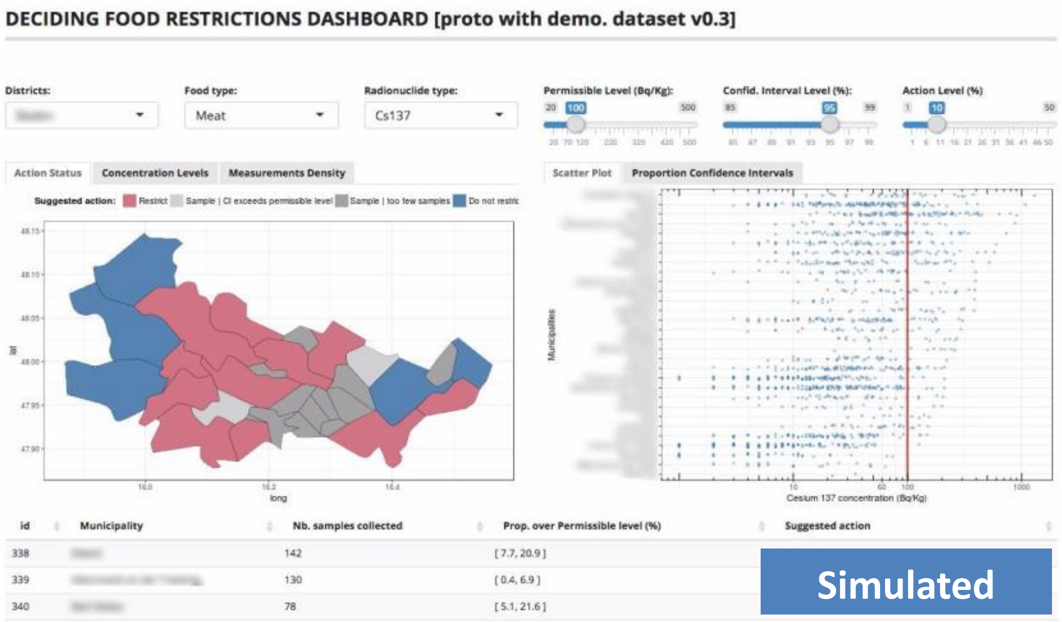
D.1.3. DSS4NAFA

165. DSS4NAFA is a cloud-based IT-DSS developed by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture to guide Agency and FAO Member States in their response during a nuclear emergency affecting food and agriculture (Figure D-1). It optimizes the collection, management and visualization of data through state-of-the-art algorithms. The specific features that set DSS4NAFA apart from the rest is that it uses modern technology such as mobile tools and advanced geographic visualization to overcome the logistical challenges encountered in a nuclear emergency and it has a user-friendly data analysis component that proposes response actions. DSS4NAFA is built in a modular way, including several IT components, which are integrated but can be exchanged separately, making the system extremely flexible and adaptable. The beta version of this tool will be available in 2018.

FIG. D-1: Use of modern IT systems to optimize and respond to nuclear emergencies affecting food and agriculture. General overview of how DSS4NAFA works.
(Source: *FAO-IAEA)*

166. DSS4NAFA is an innovative system for assessing and interpreting data on radioactive contamination in food and agriculture and enhancing the nuclear emergency response capacity of food safety authorities. It supports decision makers in determining sampling locations and assigning sample and laboratory analysis tasks. It provides powerful visual interpretation tools integrating multidimensional data, from local to international scales, collected and processed during a nuclear emergency.

167. Upon obtaining the radionuclide concentration data, the food restriction dashboard collates the information, including the spatial distribution and time resolution of the accident, and suggests food and planting restrictions based on the level of risk and the specified tolerance levels. The use of DSS4NAFA reduces the complexity in managing logistics of data collection, forecasting scenarios in data analysis, and proposing restriction actions for decision-making.



DECIDING FOOD RESTRICTIONS DASHBOARD [proto with demo. dataset v0.3]

Districts: [redacted]

Food type: Meat

Radionuclide type: Cs137

Permissible Level (Bq/Kg): 100

Confid. Interval Level (%): 95

Action Level (%): 10

id	Municipality	Nb. samples collected	Prop. over Permissible level (%)	Suggested action
338	[redacted]	142	[7.7, 20.9]	
339	[redacted]	130	[0.4, 6.9]	
340	[redacted]	78	[5.1, 21.6]	

Simulated

FIG. D-2: The restriction dashboard, a specialized module of DSS4NAFA, assists decision makers by proposing decision actions based on radionuclide concentration information and adjustable confidence-level intervals. Stakeholders can identify the administrative units to restrict, perform more sampling, or not restrict for food and planting decisions. (Source FAO-IAEA)

168. DSS4NAFA is able to manage large volumes of data, without the potential of overload to the user. Practical examples of its use include visualization of contamination data in space and time, interactive graphical images for optimized allocation use of sample collectors and use of analytical laboratory facilities, and dashboards for identifying areas where food restriction is warranted.

169. The system platform is accessible on-site through a smartphone application, or office-based via a desktop interface, allowing for streamlined usage and communications. The combination of these functionalities brings together all stakeholders in the process and increases robust emergency response capabilities.

D.2. Use of irradiation to develop novel and effective vaccines against animal and zoonotic diseases

170. The increased productivity of livestock helps millions of families around the world to increase their incomes. Availability and access to effective vaccines reduces the disease burden and is vital for livestock farming. Many diseases that are transmitted from animal to human and vice versa (zoonotic diseases) can be prevented by the use of vaccines.

171. The use of vaccines also reduces the use of therapeutics in animal farming, and contributes to reducing the load of antiparasites and antimicrobial resistance. Although biotechnological advances witnessed in the last century helped to develop many novel livestock vaccines, several devastating transboundary infectious diseases continue to burden livestock producers due to the absence of effective vaccines or the low efficacy of those currently available.

172. One of the best ways of making a vaccine is to use whole non-infectious pathogens as a means of inducing immunity. Radiation technology is applied in multiple rational ways to develop vaccines (Figure D-3). In one approach, pathogens such as viruses are subjected to a higher gamma irradiation dose (25–30 kGy) to completely inactivate the pathogen. This approach is desirable for highly pathogenic organisms where no live organisms are to be injected into the host. However, inactivation

by irradiation does not destroy antigens as compared to chemical methods, which are frequently employed in vaccine making.

173. Alternatively, a low dose of irradiation is employed to stop the replication or disease-causing ability of the organism while the organism is still metabolically active. This is due to the partial destruction or occurrence of certain mutations in the genetic material. Thus, these vaccines are termed "metabolically active and replicative defective".[7]

174. In a third approach, an irradiated pathogen is used to increase or refine the immunogenicity of another related or unrelated microorganism contained in the vaccine.

175. Compounds that augment the vaccine effectiveness are called adjuvants and they are often used in vaccine preparations. Radiation technologies can also be used indirectly to enhance the effectiveness and safety of vaccines. One such application is the irradiation of existing vaccines to ensure that no infectious, contaminating organisms are in the formulation used for inoculation. Alternatively, vaccine adjuvants can be irradiated to modify their structure (e.g. polymerization) to enhance the immunological or protection effect.

176. Since the 1950s, scientists have tried to create vaccines by irradiating pathogens. However, the classical use of irradiation technologies was to over-irradiate the pathogens, thereby destroying the nucleic and protein structures of these candidate vaccines. Our recent understanding in the use of irradiation technologies is based on the discovery that modern irradiators can generate higher and more specific irradiation doses effectively. In parallel, knowledge of the immune system has also expanded, leading to the availability of refined tools and technologies for evaluating immune responses following vaccination.

177. Together with the advances in genomic studies, these developments have caused a renaissance in irradiated vaccine research and have expanded the development of novel and effective vaccines. For example, novel electronic beam irradiators can generate an irradiation dose as high as 30 kGy within minutes, which prevents the accumulation of undesirable by-products such as free radicals, which are impossible to avoid when using a longer duration of irradiation.

178. Recently discovered radio-protective compounds also help to protect structures that are responsible for vaccine antigenicity. Among them, Mn2+-decapeptide complex (MDP), a compound isolated from radiation-resistant bacteria, preserves immunogenic proteins of viruses and bacteria exposed to higher doses of γ-rays by scavenging the free radicals produced during irradiation.[8]

179. The technological advances and creative vaccine approaches referred to above have moved beyond initial basic experiments. In human medicine, metabolically active non-replicative malaria sporozoites harvested from irradiated mosquitos have been used to induce immunity against malaria infections. A strong proof of concept and high safety standards are required for a vaccine candidate to be employed in human clinical trials.

180. The irradiated malaria vaccine has not only reached the clinical trial stages but also demonstrated significant protection against subsequent infections.[9] Irradiation has also been employed for the

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[7] Magnani, D.M., Harms, J.S., Durward, M.A., Splitter G.A., Nondividing but metabolically active gamma-irradiated Brucella melitensis is protective against virulent B. melitensis challenge in mice, Infect. Immun. 77 11 (2009) 5181-5189.

[8] Gayen, M., et al., Deinococcus Mn2+-peptide complex: A novel approach to alphavirus vaccine development, Vaccine. 35 29 (2017) 3672-3681.

[9] Sissoko, M.S., et al., Safety and efficacy of PfSPZ Vaccine against Plasmodium falciparum via direct venous inoculation in healthy malaria-exposed adults in Mali: a randomised, double-blind phase 1 trial, Lancet Infect. Dis. 17 5 (2017) 498-509.

complete inactivation of the HIV-1 virus, which then was shown to be safe in a human clinical trial and enhanced anti-HIV antibody responses.

181. Based on these positive developments and our new understanding of the selective and controlled use of irradiation, many public and private institutions have stepped up their efforts to develop "radio-vaccines". Research led by scientists from the Fraunhofer Institute for Cell Therapy and Immunology (IZI) in Germany showed that low-energy-electron irradiation maintained antigenic properties in viruses such as equine herpes and porcine reproductive and respiratory syndrome and even protective immune responses in influenza.[10]

182. Research carried out at both the University of Wisconsin-Madison and Purdue University in the United States has shown that vaccinating mice with metabolically active irradiated Brucella bacteria prevents them from falling sick when exposed to a challenge infection. Brucella is an economically debilitating disease in animals with a global economic impact, and is also a zoonotic disease. These are only a few examples of successful experiments that have been carried out when developing irradiated vaccines for livestock diseases. Other ongoing experiments to develop irradiated vaccines for transboundary animal diseases include foot-and-mouth disease and haemorrhagic septicaemia.

183. The Agency has pioneered a new generation of research in this area through a coordinated research project involving six counterparts (Bangladesh, Egypt, Ethiopia, the Islamic Republic of Iran, Sri Lanka and the Sudan) to evaluate new approaches to produce experimentally irradiated vaccines (Figure D-4).

184. Scientists from these countries address different animal or zoonotic pathogens and have proven concepts of differential irradiation doses towards the development of vaccine candidates. Currently, experiments are being carried out to determine if such vaccines could protect an animal when challenged with the infectious pathogen. The first breakthrough was reported with a prototype irradiated vaccine for Haemonchus contortus, a gastro-intestinal parasite of ruminants. The challenged animals were 100% protected following two oral doses of irradiated Haemonchus contortus larvae.

185. The Agency is conducting experiments to develop prototype irradiated vaccines against two swine viruses severely affecting pig farming: swine influenza and porcine reproductive and respiratory syndrome. It is also developing and providing tools that measure immune responses induced following vaccination with irradiated organisms. Techniques are being developed that measure cell-mediated immunity, an area that has been poorly developed in livestock immunology but is important when studying viral diseases.

186. The Agency is also developing a repository of monoclonal antibodies that recognize bovine immune markers, which will be distributed to Member State laboratories. Referring to specific pathogens, scientists recently discovered "hot spots" of the genome of Trypanosoma parasites that are affected by low dose irradiation. This discovery will aid in designing drugs and vaccines against a parasite that has far-reaching effects on livestock production in developing countries.

187. With the differential irradiation technology concept proven and established, research is now concentrating on process development and scaling up of vaccine production. Sanaria, a biotechnology company experimenting on the irradiated malaria vaccine is exploring using robots to produce vaccines, while the Fraunhofer Institute in Germany is experimenting on developing a novel automated technical procedure to transfer e-beam irradiation to an industrial scale for vaccine production. Some of the counterparts in the coordinated research project have taken initiatives towards making dry formulations

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[10] Fertey, J., et al., Pathogens inactivated by low-energy-electron irradiation maintain antigenic properties and induce protective immune responses, Viruses 8 11 (2016) E319.

of the irradiated vaccine to achieve thermostability, which could aid delivery to remote areas without maintaining vaccines in cold-chain.

188. Although many developments of irradiated vaccine technology are only in the research phase, current discoveries strongly demonstrate the potential application of the technology for developing effective vaccines against many disease-causing viruses, bacteria and parasites. Investing in this technology will aid in controlling many diseases and could have a major impact on the economies and health of developing countries.

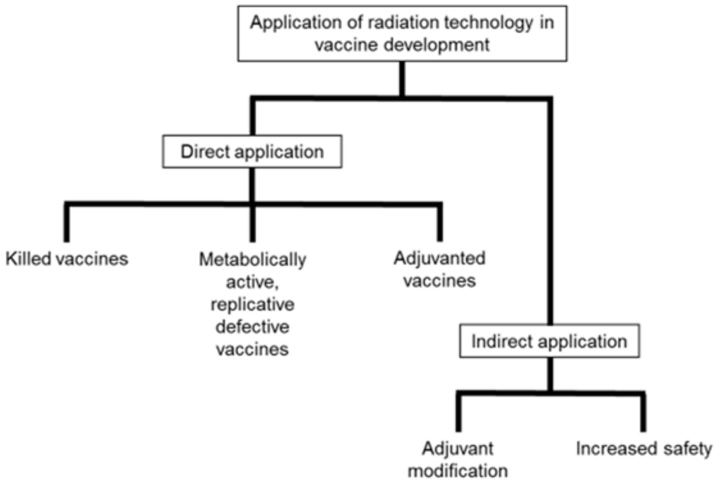

FIG. D-3. Radiation technology can be applied to develop new vaccines and enhance the efficacy and safety of existing vaccines. (Source: IAEA-FAO)

FIG. D-4. In the Islamic Republic of Iran, a scientist is formulating an irradiated vaccine (left) while a scientist from Sudan draws blood from a sheep (right) to evaluate the efficacy of a vaccine. (Photo credit: Farahnaz Motamedi-Sedeh, Nuclear Science and Technology Research Institute, Islamic Republic of Iran, and Mihad Alawad, Central Veterinary Research Laboratory, Sudan)

D.3. Multi-isotope Fingerprints to Identify Sources of Agro-contaminants from Soil to Water Bodies

189. The Agency is currently working to develop protocols and guidelines for tracing the sources of agropollutants, and to develop innovative soil and water management practices to reduce agropollutants in the environment.

190. Agricultural pollution of rivers and streams has direct negative impacts on human health, biodiversity and fisheries. The expansion and intensification of agricultural systems in response to the ever-increasing demand for food often lead to overuse and misuse of agrochemicals such as organic and inorganic fertilizers and pesticides. Globally, high crop production has been achieved mainly through the intensive use of agrochemicals with irrigation contributing to the transfer of agricultural pollutants from soil to water bodies. In most high income countries and in many emerging economies agricultural pollution already exceeds pollution from households and industries as the major cause of degradation of inland and coastal waters. In the European Union, 38% of water bodies are under significant pressure from agricultural pollution[11] (Figure D-5). In the United States of America, agriculture is the main source of pollution in rivers and streams, the second main source in wetlands and the third main source in lakes.[12]

191. A major knowledge gap regarding pollution in agro-ecosystems is source identification and apportionment, an area that requires more data, research and integration of approaches. Identifying and apportioning these contributions is essential in order for national agencies and governments to design appropriate policies and management practices and to target responses. When pollution through multiple sources to an agro-ecosystem occurs, traditional techniques, such as quantification of the polluting element and mass balance, are not effective in evaluating the relative contribution of the different sources. Therefore, complementary approaches are needed to address these gaps. Complementing conventional approaches, stable isotopes of the major chemical elements are key to characterizing and quantifying sources and the transport of solutes through soil and water bodies in agro-ecosystems.

192. Stable isotopes of the chemical elements nitrogen, carbon, oxygen, sulphur and hydrogen have been successfully used to trace and monitor sources and transport of solutes and water in agro-ecosystems.[13] Studies have shown that depending on the origin of the polluting source, the isotopic signature of each element is unique and can thus be used to fingerprint the source. In order to trace and monitor the sources of phosphorus, a key fertilizer that boosts crop productivity, from the soil to water bodies, the oxygen-18 isotope signature in inorganic phosphate (δ18O-PO4) is used. Application of compound specific isotope analysis (CSIA) to micropollutants relies on the ability to monitor changes in stable isotope composition between source(s) and outlet(s) and hence to quantify the extent of chemical or biochemical conversion in agro-ecosystems.[14,15,16] The multiple sources of pollutants in agro-ecosystems could present overlapping isotopic signatures, making their identification and apportioning difficult, if not impossible, with a single isotope tracer.

193. Full characterization of the potential multiple sources of macronutrients and micropollutants in complex agro-ecosystems requires an integrated multi-tracer approach. The stable carbon, oxygen, nitrogen and sulphur isotope signatures of the solutes characterize the proportional contribution from

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[11] WWAP (United Nations World Water Assessment Programme) (2015). The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris, United Nations Educational, Scientific and Cultural Organization.

[12] US EPA (United States Environmental Protection Agency) (2016). Water Quality Assessment and TMDL Information. https://ofmpub.epa.gov/waters10/attains_index.home.

[13] Skrzypek G., Mydłowski A., Dogramaci S., Hedley P., Gibson J.J., Grierson P.F. (2015). Estimation of evaporative loss based on the stable isotope composition of water using Hydrocalculator. Journal of Hydrology 523: 781-789. https://doi.org/10.1016/j.jhydrol.2015.02.010.

[14] Tamburini F., Pfahler, V., von Sperber, C., Frossard E., Bernasconi, S.M. (2014). Oxygen isotopes for unravelling phosphorous transformations in the soil-plant systems: a A review. Soil Science Society of America Journal 78: 38-46.

[15] Granger, S.J., Harris, P., Peukert, S., Gou, R., Tamburini, F., Blackwell, M.S.A., Howden, J.K., McGrath, S. (2017). Phosphate stable oxygen isotope variability within a temperate agricultural soil. Geoderma 285: 64-75.

[16] Elsner M., Imfeld, G. (2016). Compound-specific isotope analysis (CSIA) of micro pollutants in the environment - current developments and future challenges. Curr. Opin. Biotechnol. 41:60–72.

various sources while the stable hydrogen and oxygen isotopes of water molecules characterize the water cycle (sources of water and evaporative losses). This integrated approach to the analysis of solutes and water allows separation of the pathways of pollutant dispersal and water flow. The advantage of the application of stable isotope techniques is that they provide an inexpensive analytical alternative to the usually laborious and time-consuming full-scale monitoring that requires well-established infrastructure. The Joint FAO/IAEA Division has therefore initiated a coordinated research project to develop and validate guidelines for the use of multiple stable isotope tracers to monitor soil, water and nutrient pollutants from agriculture at field and landscape scales.

194. When integrated with conventional techniques, this approach should facilitate the adoption of appropriate remediation measures in Member States and result in better and more sustainable land management practices.

FIG. D-5. Left: Schematic diagram of pollutants from agriculture in an agro-ecosystem environment (Photo credit: Gwenaël Imfeld, CNRS, France). Right: Water quality in the Danube Delta affected by pollutants (Photo credit: IAEA-FAO)

E. Human Health

E.1. Stereotactic Radiotherapy: A High-precision Radiotherapy Technique

195. Stereotactic radiosurgery (SRS) is a non-surgical advanced radiation technique for delivering precisely targeted radiation to tumours and some functional abnormalities of the brain. Stereotactic body radiotherapy (SBRT), sometimes called stereotactic ablative radiation therapy (SABR), is an extension of the same technique for delivering radiation to extra-cranial sites of the body.

196. In SRS or SBRT, the entire dose is delivered in one to five sessions, whereas, in conventional radiotherapy, the dose is delivered in a number of small daily fractions spread over several weeks. Both techniques are important alternatives to invasive surgery, particularly for patients who cannot undergo surgery and for tumours and abnormalities that are difficult to reach or close to vital organs. There is no incision, minimal discomfort, shorter recovery times and few of the risks typically associated with surgery, such as infection.

197. Expertise in disease site and equipment is required for implementing SRS and SBRT. Therefore, a workflow should be designed for SRS and SBRT that is specific to the disease site and equipment being used.

E.1.1. Technical requirements

198. An SRS or SBRT programme requires adequate staffing to ensure its safety and quality. The margin of error with these techniques is smaller than that with conventional radiotherapy because higher doses are used per fraction and there are fewer fractions. Therefore, the machine used to deliver such treatment must meet the most stringent technical requirements, including those for mechanical tolerance and commissioning. Before actual treatment, the entire treatment process is tested end-to-end on a phantom. SRS and SBRT typically involve imaging, immobilization and planning and treatment delivery, as outlined below.

Three-dimensional imaging and four-dimensional tumour localization

199. High-resolution imaging defines tumour location, size and shape, helps determine the exact coordinates of the target (tumour) within the body and guides treatment planning. Computed tomography (CT), magnetic resonance imaging (MRI) and positron emission tomography (PET)/CT are used for this purpose. Generally, a CT scan is used for baseline imaging. It provides accurate information on electron density and generally has very low spatial distortion. For many SBRT targets, e.g. lung and abdomen, PET-CT and, in cases of brain lesions and liver lesions, MRI are the preferred imaging tools, as they allow better demarcation between normal and abnormal tissues than CT.

Immobilization, positioning and maintenance of the position of the patient

200. During imaging and treatment, tumour position may change due to respiration or body movements, or the tumour may undergo changes in shape and size. As this type of treatment requires millimetre accuracy, patient-specific, customized immobilization devices are required to keep patients immobilized and thus minimize movement of the target during treatment. Many methods exist to assess, manage and monitor respiratory motion during SBRT, including slow CT, 4-D CT, abdominal compression, gating and breath-holding techniques. 4-D CT imaging allows reconstruction of an internal target volume that takes into account the tumour position at all phases of the respiratory cycle. Real-time dynamic target tracking is also possible.

Highly focused gamma-ray or X-ray beams

201. SRS and SBRT can be delivered with a linear accelerator, a gamma knife unit or a charged-particle accelerator. Linear accelerators can treat larger tumours in a single (SRS) or multiple sessions (stereotactic radiotherapy).

202. The gamma knife device was invented by Leksell, a Swedish neurosurgeon, in Sweden in 1951 and was the first device used to deliver SRS. It has multiple cobalt radiation sources that create beams of highly focused gamma rays, all aimed at the target region. It is ideal for treating small to medium-sized intracranial lesions, usually less than 4 cm, with attention to avoiding high doses to structures such as the optic apparatus and brainstem.

203. The main advantage of heavy charged particle proton SRS is that beams stop at a depth related to their energy. The absence of an exit dose and the sharp beam profile of protons allow targeted irradiation with a lower integral dose than those delivered by photon irradiation. This is an expensive form of treatment.

E.1.2. Team required

204. A team of highly skilled, multidisciplinary personnel is required for the delivery of SRS and SBRT, including radiation oncologists, medical physicists, radiotherapy technicians, radiologists,

neurosurgeons and neurophysicians. Radiation oncologists lead the treatment team; occasionally, neurosurgeons have a co-leadership role.

205. The radiation oncologist outlines the target to be treated and normal tissues, prescribes the appropriate radiation dose, approves the treatment plan and interprets the results of radiosurgical procedures. The medical physicist ensures delivery of the precise dose of radiation; he or she uses a computerized treatment planning system to devise treatment plans and to calculate the exposure time and the beam configuration to treat the target(s) at the prescribed dose. The radiotherapy technician positions the patient on the treatment table and operates the machine.

E.1.3. Indications

206. Many benign, malignant and functional disorders of the brain are treated by SRS. SBRT has been used in a variety of indications, including early-stage lung cancer in medically inoperable patients and those who refuse surgery, lung metastases, primary liver cancer, liver metastases, organ-confined prostate cancer, pancreas cancer, adrenal metastases, primary kidney cancer in medically inoperable patients, selected intrathoracic and intra-abdominal lymph node metastases, recurrent and primary head-and-neck cancers, spinal tumours and vertebral bone metastases.

207. After treatment, benign tumours may take 18 months to 2 years to shrink, while malignant and metastatic tumours shrink more rapidly. Many tumours remain stable and inactive, with no change, and may, over time, either stabilize or regress. As a treatment option that is non-invasive and usually completed in the outpatient setting within a day or a week, SRS and SBRT can not only potentially save hospital resources but may allow patients to resume regular daily activities more quickly. The side effects of treatment depend on the tumour site and dose used. Fortunately, the side effects of SRS and SBRT are expected to be within acceptable limits.

E.1.4. Contributions of the Agency

208. In 2014, the Agency initiated a coordinated research project, a randomized study of SBRT versus transarterial chemoembolization in hepatocellular carcinoma. Eleven cancer centres in the Asia-Pacific region, Africa and Europe are participating in this study. In addition, the Agency is supporting a regional project for clinical application of SBRT and is helping Member States to initiate or upgrade their SBRT services. Many radiation oncologists, medical physicists and radiation therapists in participating counties have been trained on various aspects of SBRT, including quality assurance and quality control.

209. SRS/SBRT is widely accepted and increasingly used. Published results from well-conducted clinical studies have established their role in various clinical settings. Furthermore, SRS/SBRT is being evaluated in a large number of clinical trials, either alone or in combination with targeted agents or immunotherapy, in many primary and secondary cancers. The preclinical data show that immunotherapy can augment radiation-mediated local tumour response, and, similarly, high-dose radiation can augment the systemic effects of immunotherapy, making SRS/SBRT an ideal modality for combination with immunotherapy. SRS/SBRT may be a more cost–effective treatment than conventional radiotherapy in many clinical settings.

E.2. Neuropsychiatry: Revolution of Molecular Imaging in Alzheimer's Disease

E.2.1. Background

210. Dementia is a progressive, largely irreversible neurodegenerative disease that is characterized by impairment of mental function; it affects memory, thinking, behaviour and the ability to perform

everyday activities. Of the estimated 47 million people with dementia throughout the world, two thirds live in developing countries.

211. Distinctive clinical symptoms may be difficult to diagnose in early stages; however, nuclear techniques can be instrumental in identifying the underlying disease process several years before symptoms are seen.

212. There are many different types of dementia, Alzheimer's disease (AD) being the most common, accounting for approximately 60–70% of cases worldwide. Other common types of dementia include vascular or multi-infarct dementia, which accounts for approximately 25%; Lewy body dementia, which accounts for 15%; and frontotemporal dementia. Dementia can be also caused by diseases such as Parkinson's, syphilis and Creutzfeldt–Jakob. One person may have more than one type of dementia.

213. Disorders such as AD, which is the most feared disease after cancer, represent a substantial burden throughout the world and have a considerable medical and socio-economic impact. Dementia is one of the major causes worldwide of disability and dependence among older people.

214. Although there is no known cure for dementia, various specific approaches are available for the management of symptoms, planning care and guidance for caregivers and family members, depending on the cause. In addition, some medications may be beneficial in early stages, thus delaying progression of the disease; and other measures can improve the quality of life of people with dementia and their caregivers. Earlier, more accurate differential diagnosis is therefore essential for improving patient care.

215. Dementia is usually diagnosed by an evaluation of the history of illness and the results of cognitive tests designed to show conscious intellectual activity, such as thinking, reasoning or remembering. The detection of possible cognitive impairment is the first step in determining whether a patient should undergo further evaluation.

E.2.2. Diagnosis

216. Nuclear medicine, also known as molecular imaging, has developed significantly over the past few decades. Since the 1990s, positron emission tomography (PET) brain imaging with the radiopharmaceutical fluorodeoxyglucose (FDG) and brain perfusion single positron emission computed tomography (SPECT) imaging have been instrumental in clinical diagnosis of various brain disorders, including AD and other forms of dementia.

217. Molecular imaging studies are helpful in complex cases of dementia and when other conditions are also present and it is not immediately clear to which disease a symptom should be attributed. Stroke is a common comorbid condition. It can influence brain function on its own, and some of the symptoms are similar to those caused by neurodegenerative dementia. Molecular imaging allows doctors to differentiate between these conditions.

218. PET is a well-established means for evaluating patients with neurodegenerative disorders, especially in the diagnosis of dementia. When FDG is used, the glucose metabolism of the brain can be evaluated, allowing early, appropriate diagnosis, differential diagnosis, early recognition of progressive dementia, monitoring of disease progression and evaluation of the response to drug treatment.

219. Tracers also offer new perspectives for studying the neuropathology of underlying dementia, such as the accumulation of amyloid proteins, tau proteins, and the presence of inflammation or vascular disorders. PET imaging with different tracers offers reliable biomarkers in dementia, which can assist clinicians in diagnosing various dementing disorders, especially in the case of overlapping diseases.

220. Recently, amyloid PET imaging has become available in clinical settings in many countries. Amyloid PET scans allow accurate detection in vivo of amyloid plaques, one of the fundamental

pathological processes of AD. The scan, which is extremely specific for evaluating abnormal protein deposits in the brain, may help improve recommendations for diagnosis and treatment. Its clinical value is currently being evaluated in multi-centre trials.

221. Other new PET imaging techniques are evaluation of tau protein and inflammation. Tau is a microtubule-associated protein that is essential to neuronal stability and functioning, and its hyperphosphorylation and abnormal aggregation are implicated in various neurodegenerative diseases, known as ‘tauopathies’. The most common of these is AD.

222. These techniques not only improve day-to-day patient care but also provide critical knowledge of the disease process itself, which will help improve therapeutic developments.

E.2.3. Global initiatives and awareness

223. Several global initiatives address the burden of dementia. Some of the most important are: identification of dementia as a global priority, rapid development of neuroimaging and medical research for new treatment alternatives. In addition, some organizations are including dementia on their agendas, such as the G7 with its Global Action Against Dementia initiative, the WHO Ministerial Conference on Global Action Against Dementia and, more recently, the Bill and Melinda Gates Foundation.

224. The Agency is involved in current developments and activities to raise awareness about the importance of dementia and other neurological diseases. The activities include coordinated research projects, regional training courses and national workshops on the importance of nuclear medicine techniques in imaging cerebrovascular and neurological diseases, including dementia. The Agency has established the IAEA Neuroimaging Consortium to investigate the value of neuroimaging with modern techniques such as PET–CT to properly diagnose mild cognitive impairment and to determine whether the presence of comorbid conditions such as HIV infection, cerebrovascular disease and traumatic brain injury results in less accurate diagnosis than in patients without these comorbid conditions. Currently, there is limited scientific evidence in this subset of patients; therefore, new information will be of benefit to Member States. The IAEA Curricula for Nuclear Medicine Professionals workshops, held at Osaka University Graduate School of Medicine in Japan, focused on the importance of nuclear medicine techniques in the imaging of cerebrovascular and neurological diseases, including brain tumours, epilepsy and dementia. Workshops on neuroimaging to enhance the skills of nuclear medicine physicians in interpreting studies of nuclear neurology that include dementias have also been conducted in Argentina, Brazil, the Philippines, Slovenia and Thailand.

225. In support of continuous medical education, the Agency’s Human Health Campus website has a section devoted to neuroimaging, which offers visitors teaching cases, lectures, a recommended bibliography and guidelines, a guide to reporting medical scans and educational materials used in Agency training courses.

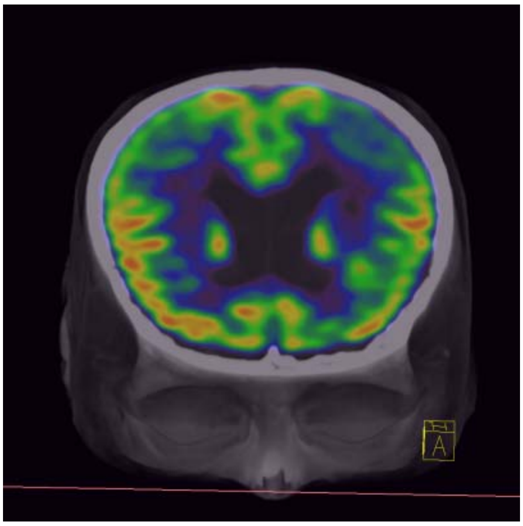

FIG E-1. Volumetric reconstruction of a PET/CT study in a diabetic, 65 years old, female patient with Alzheimer's disease. The nuclear medicine PET/CT study was performed with 18F-FDG to establish the type of dementia and extent of the disease. (Photos: Dr Ivan Diaz, Nacional Institute of Neurology and Neurosurgery in Mexico)

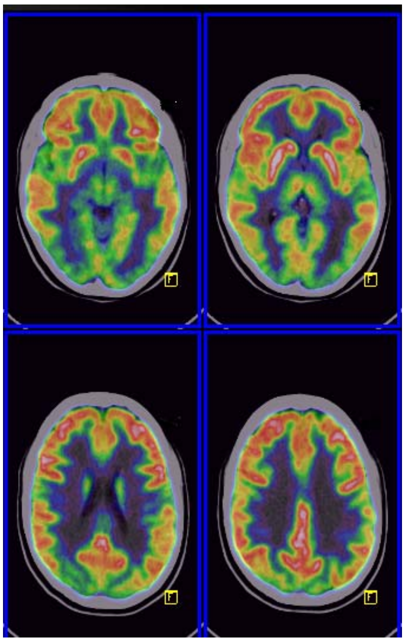

FIG E-2. 75 Years old, male patient with history of Hypertension, and clinical signs of dementia. The nuclear medicine PET/CT study was performed with ^{18}F-FDG to establish the type of dementia and extent of the disease. The scan confirms changes associated to Alzheimer's disease (Photos: Dr Ivan Diaz, Nacional Institute of Neurology and Neurosurgery in Mexico)

F. Environment

F.1. Nuclear Techniques in Marine Plastics Research

226. Oceans cover more than 70 per cent of the Earth's surface, and are unequivocally tied to defining its hospitable climate and to mitigating some of the negative effects of climate change. If managed well, oceans may also play an important role in providing jobs and sustenance for large sectors of the world's population. Unfortunately, oceans are also the final repository for much land-based pollution, including

diverse agricultural, municipal, and industrial discharges of organic and inorganic contaminants. As a derivative of such activities, plastic fragments of all sizes are now found ubiquitously in the ocean, where marine animals, such as benthic organisms, zooplankton, molluscs, fish, seabirds and whales, may ingest the smaller-sized particles. While the high-profile, visible impact of macro-plastics on marine organisms has been well documented, the potential harm caused by micro-plastics, defined typically as particles smaller than 5 mm in diameter, [17,18] is much less clear (Figure F-1).

FIG. F-1. Plastic debris including micro-plastics are now present everywhere in the ocean and may be ingested and bioaccumulated by diverse marine organisms where they can pose a health risk to humans. Photo credit: J.L. Teyssie/IAEA.

227. In order to help inform and develop better mitigation strategies and tools, the Agency is using nuclear and isotopic techniques to assess the impact of common and emerging environmental stressors, including the effects of plastics on marine organisms. Currently, such techniques are being developed to quantify the movement of marine micro-plastics and associated organic contaminants within coastal and marine ecosystems and their inter-related food-webs. Some organic contaminants are effectively scavenged onto plastic surfaces from seawater; these micro-plastics and their associated contaminants pose additional threats to marine organisms.[19] Nuclear techniques enable the study of 'sorption kinetics', or how organic pollutants attach themselves to the micro-plastic hosts, as well as contaminant degradation processes and rates. When used in controlled experimental aquaria, these methods deliver quantitative data that can provide a unique window into the biological impacts of marine microplastics.

228. Marine plastics are synthetic organic polymers that are typically inexpensive to produce and by design highly durable. All plastics eventually become brittle and break down into smaller fragments that can degrade further when exposed to sustained ultraviolet radiation. The most abundant polymers found in the ocean are high- and low-density polyethylene, polyvinyl chloride, polystyrene, polypropylene and polyethylene terephthalate. Together, these polymers account for more than 95 % of the global plastics

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[17] Andrady, A.L., Microplastics in the marine environment. Marine Pollution Bulletin 62, 1596–1605. This publication is referred to several times in Section F.

[18] United Nations Environment Programme, Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change. UNEP, Nairobi (2016). This publication is referred to several times in Section F.

[19] Law, K.L., Thompson, R.C., Microplastics in the seas. Science 345, 144-145. This publication is referred to several times in Section F.

production.[20] As they are specifically designed to resist corrosion, most of these plastics are regarded as "hard-to-degrade" and persist in the marine environment for 100 years and more.

229. Micro-plastic particles are found in many marine organisms, including species we depend on and consume as part of our regular diet, such as many molluscs and finfish. Due to their small size, these plastic particles may become deposited in select internal organs where they can become effective vectors for the chemical transfer of contaminants.[21] In addition to the adverse effects caused by simply ingesting micro-plastics, secondary toxic effects may also occur as scavenged contaminants become dissociated from the micro-plastics within organs, and may undergo subsequent biochemical transformations (Figure F-2). An example of adverse biological impacts from micro-plastics includes endocrine disruption (i.e. altered gene expression) which has been observed in some fish that have inadvertently ingested plastic compounds.[22] There still remain significant gaps in our understanding of the fate and toxicity of micro-plastics and associated contaminants in humans, which new research conducted by the Agency will attempt to address.

FIG. F-2. Ingestion of micro-plastics by marine biota, including mussels, worms, fish, and zooplankton (as shown here) remains under-researched. Cole, M. et al. (2013). Microplastic ingestion by zooplankton, Environ. Sci. Technol., 2013, 47 (12), pp 6646–6655.

230. Laboratory-based nuclear techniques will provide critical new information on the interactions and impacts of a wide range of plastic micro-particles and their associated toxic contaminants, including persistent organic pollutants (POPs) and trace elements, such as mercury, cadmium and lead.

231. Radioisotopes are uniquely suited to quantify the movement and biological impacts of micro-plastics and their associated contaminants. Experiments that utilize radioisotopes as tracers for microplastics can be designed using ambient concentrations and commercially-important marine organisms. In this manner, a radiolabelled microplastic particle can be used to track realistic rates of

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[20] Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin 62, 2588–2597.

[21] Engler, R.E., The Complex Interaction between Marine Debris and Toxic Chemicals in the Ocean. Environmental Science and Technology 46, 12302−12315.

[22] Lusher, A.L., Hollman, P.C.H., Mendoza-Hill, J.J., Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety. FAO Fisheries and Aquaculture Technical Paper 615. Rome.

uptake within an organism, including information on micro-plastic degradation processes over time. Similarly, these radiolabelling techniques can be used to quantitatively assess intra-organismal biochemical transformations and eventual depuration biokinetics.

232. Complementary analytical methods, such as compound specific mass spectrometry or high resolution inductively coupled mass spectrometry, that use the isotopic signature of contaminants to track their sources and pathways can be applied to complete the picture. Therefore, application of nuclear and isotopic techniques can provide a unique opportunity to address important outstanding questions on the biological impacts of micro-plastics, including, for example, the potential effects on aquatic species at different life stages; an assessment of impacts to populations, communities and ecosystems; an understanding of the internalization kinetics (e.g. transfer across the gut wall); and a better assessment of the role as important vectors for exposure and bioaccumulation of adsorbed persistent organic pollutants and trace metals.

233. Information collected from this new research will advance the understanding of the role of micro-plastics and their associated organic contaminants in societally- and commercially-important marine organisms, and help strengthen Member State seafood safety/security programmes that must rely on accurate and timely monitoring of food health.

G. Radioisotope Production and Radiation Technologies

G.1. Alpha Therapy: New Therapeutic Applications of Radiopharmaceuticals Containing Alpha Emitters

234. Therapeutic radiopharmaceuticals contain radioisotopes that emit energetic particles which deposit their energy fairly quickly on the matter they encounter — a property known as high linear energy transfer (LET). The range of travel of the particulate radiation and the rate at which it deposits energy on the matter depends both on the energy and the mass of the particle. Beta particles, which are essentially electrons, travel much further than alpha particles of the same energy. In other words, alpha particles, which are almost 7 300 times heavier than electrons, deposit their energy within a much shorter range than beta particles of the same energy. Therefore, the LET of alpha particles is far higher than those of beta particles.

235. The first generation of therapeutic radiopharmaceuticals, labelled with radioisotope-emitting beta particles, such as iodine-131, have been used in the management of patients suffering from cancer and other diseases for several decades. Although beta particles have been effective in killing cancerous cells owing to their long range, typically ranging in millimetres in tissue, they can still damage neighbouring healthy cells even under optimized conditions. On the other hand, alpha particles have higher LET and a shorter traveling range in living tissue, typically just a few micrometres. Therefore, they provide a better choice to specifically irradiate the target cells which are usually in the range of micrometres. The alpha radiopharmaceutical therapy would be a successful approach should the alpha-emitter radiopharmaceutical be located close to the target cell nucleus, considered the subcellular target. Here, the challenge is to place the alpha emitter adequately close to the target cells to cause the desired targeted damage.

236. Various alpha emitter radionuclides that have a potential for use in radiopharmaceuticals are listed in Table 1. Over the past decades, numerous efforts to achieve effective alpha emitter-based radiopharmaceuticals have yielded some very promising results.

Table G-1. Alpha emitter radionuclides and their applications

Radionuclide	Half-life	Production	Application
Ac-225	10 d	U-233 decay chain Th-229 (alpha decay) Ra-226 (p,2n)	Peptide radionuclide therapy
Ra-224	3.66 d	Th-228 (alpha decay)	Palliative therapy in patients suffering from breast and prostate cancer with skeletal metastases
Ra-223	11.4 d	Ac-227 decay chain Th-227 (alpha decay)	
Bi-213	45.6 min	Ac-227 decay chain Ac/Bi generator	Peptide radionuclide therapy
Bi-212	60 min	Ac-227 decay chain Ra-Bi/Pb generator	Peptide radionuclide therapy (potential)
At-211	7.2 h	Bi-209 (alpha, 2n)	Radioimmunotherapy

G.1.1. Radium-223

237. Radium-223 chloride is one of the first generation of alpha emitter radiopharmaceuticals. It is an attractive alpha emitter radiopharmaceutical because it is a simple chemical inorganic molecule that is easy to prepare and understand. In 2013, radium-223 chloride received approval by the US Food and Drug Administration for use in bone pain palliation and has been commercially available by the name of Xofigo ever since. Radium, which is chemically similar to calcium, naturally accumulates in the bone tissue very efficiently. Radium-223 chloride has excellent performance as a therapeutic radiopharmaceutical for palliation of pain suffered by patients with skeletal metastases. It is currently used for the management of patients suffering from prostate and ovarian cancer with metastases. However, a limited number of producers and the technical complexity of producing radium-223 have led to its limited availability, high cost and lower accessibility in most countries, particularly developing countries.

G.1.2. Actinium-225/Bismuth-213 generator

238. The experience with radium-223 chloride propelled research towards the development of radiopharmaceuticals that could be used to target tumours other than bone metastases by using targeting molecules, such as peptides and antibodies. The quest for a multi-valent alpha emitter radionuclide that could be used to label peptides/antibodies led to the exploration of the alpha emitter bismuth-213, with a 45.6 minute half-life, as a ‘theranostic’ radionuclide, i.e. serving both diagnostic and therapeutic roles). Considering the short half-life and limitations for direct production of bismuth-213, an actinium-225/bismuth-213 generator is the best approach for producing bismuth-213 for use in hospital radiopharmacies. The actinium-225/bismuth-213 generator is available with high specific activity and, owing to favourable chemical and physical properties, is already used in a large number of preclinical studies and several clinical trials. This system demonstrates feasibility, safety and therapeutic efficacy of targeted alpha therapy using peptides and immunomolecules as targeting agents.[23] The methods to produce actinium-225 using an actinium-225/bismuth-213 radionuclide generator have been well

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[23] Morgenstern, A., Bruchertseifer, F., Apostolidis, C., Bismuth-213 and actinium-225 -- generator performance and evolving therapeutic applications of two generator-derived alpha-emitting radioisotopes, Curr Radiopharm. 5(3) (2012) 221-227.

established in some research institutes. However, the generator is still not widely available due to the limited number of producers. The current production at the research institutes covers just the limited demand from ongoing clinical trials.[24] A market evaluation and demand overview are necessary to clarify actual market demands.

G.1.3. Actinium-225

239. Actinium-225 has recently been directly labelled and used in clinical applications and has shown strong potential as a theranostic radiopharmaceutical. Actinium-225 attached to a prostate cancer cell targeting moiety, namely the prostate-specific membrane antigen (PSMA), has been used for therapy of patients suffering from advanced-stage prostate cancer. The results (shown in Figure G-1) attracted worldwide interest for this radiopharmaceutical. One of the issues related to the preparation and distribution of actinium-225 PSMA is the production and availability of actinium-225 because all production routes have certain disadvantages. In order to satisfy the potential large demand foreseen for actinium-225 in the near future, all these must be addressed. Canadian Nuclear Laboratories is constructing a generator based on mCi of thorium-229, capable of producing tens of mCi of actinium-225 annually.

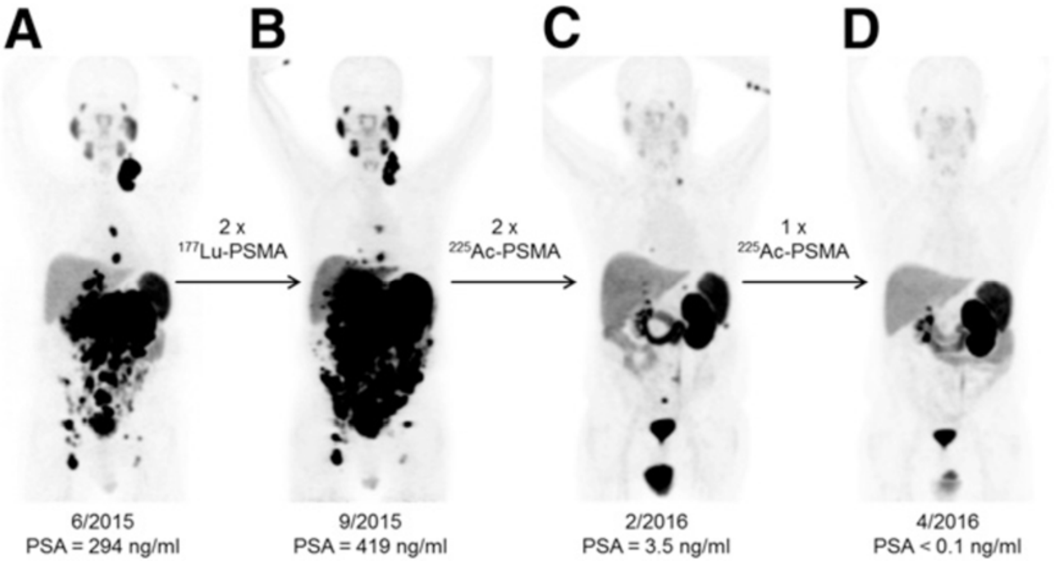

FIG. G-1. ^{68}Ga-PSMA-11 PET/CT scans of patient in comparison to initial tumour spread (A), restaging after 2 cycles of β-emitting ^{177}Lu-PSMA-617 presented progression (B). In contrast, restaging after second (C) and third (D) cycles of α-emitting 225Ac-PSMA-617 presented impressive response.[25]

G.1.4. Astatine-211

240. Another well-known alpha emitter with suitable properties for use in radiopharmaceuticals is astatine-211. Astatine-211, a halide radionuclide, has production limitations owing to the use of rarely available alpha particle accelerating cyclotrons, low yields and low labelling efficacy. This has limited

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[24] McDevitt, M.R. et al., An 225Ac/213Bi generator system for therapeutic clinical applications: construction and operation, Appl Radiat Isot. 50 (1999) 895–904.

[25] Clemens Kratochwil, C. et al., 225Ac-PSMA-617 for PSMA-Targeted a-Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer, J Nucl Med 57 (2016) 1941–1944.

its application over the past decade.[26] Until now, no clinical trial of radiopharmaceuticals based on this radionuclide has been reported. Consequently, the challenge to overcome production and availability issues, as well as to facilitate a routine radiopharmaceutical production process continues.[27]

241. The recent successes in the use of alpha emitting radiopharmaceuticals have kindled keen interest in use of such molecules in treatment of cancers. Exploring their use in a sustained manner around the world is relevant and timely.

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[26] Elgqvist, J., Targeted alpha therapy: part I. Curr Radiopharm. 4(3) (2011) 176.

[27] IAEA, Report of the Technical Meeting on Alpha emitting radionuclides and radiopharmaceuticals for therapy (2013)http://www-naweb.iaea.org/napc/iachem/working_materials/TM-44815-report-Alpha-Therapy.pdf.

IAEA
International Atomic Energy Agency

www.iaea.org

International Atomic Energy Agency
Vienna International Centre, P.O. Box 100
1400 Vienna, Austria
Telephone: (+43-1) 2600-0
Fax: (+43-1) 2600-7
Email: Official.Mail@iaea.org

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