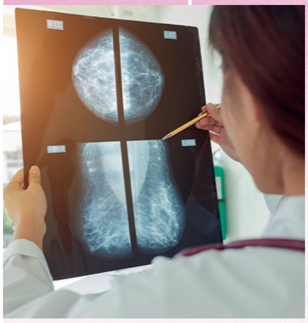
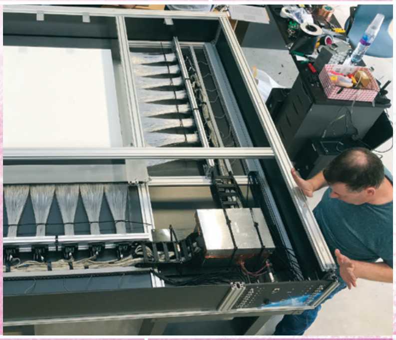
NUCLEAR TECHNOLOGY REVIEW

2019





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Nuclear Technology Review 2019

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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 2019* highlights notable developments in the world in 2018, in the following select areas: power applications, atomic and nuclear data, accelerator and research reactor applications, nuclear techniques in food, soil and livestock management, cancer diagnosis and therapy, new developments in the study of isotopes in precipitation, ocean acidification effects and cultural heritage preservation.

The draft version was submitted to the March 2019 session of the Board of Governors in document GOV/2017/2. 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 2018, the 450 operational nuclear power reactors had a record global generating capacity of 396.4 GW(e), which was an increase of 5 GW(e) compared to 2017. In 2018, nine reactors were connected to the grid, seven were permanently shut down, and construction started on five. Near and long term growth prospects remained centred on Asia, which is home to 35 of the 55 reactors under construction, as well as 58 of the 68 reactors that have been connected to the grid since 2005.

2. Of the 30 Member States currently operating nuclear power plants (NPPs), 14 are either constructing new reactors or completing previously suspended construction projects. Another 28 countries are considering, planning or actively working to include nuclear power in their energy mix. Four newcomer countries are building their first NPPs and several others are at advanced stages of infrastructure preparation.

3. The Agency's 2018 high projections for global nuclear power capacity show a 30% increase over current levels by 2030 and almost a doubling of capacity by 2050, while, in the low projections, capacity continues to decline for around a decade before rebounding to 2030 levels by 2050. The emissions pathways presented in an Intergovernmental Panel on Climate Change special report reflect the need to substantially expand the contribution of nuclear power to climate change mitigation.

4. The 26th edition of the biennial 'Red Book', an authoritative world reference report, shows that the world's supply of uranium is more than adequate to meet projected requirements for the foreseeable future, regardless of the role that nuclear energy ultimately plays in meeting future electricity demand and global climate objectives. However, low uranium prices continued to restrict the ability of companies to invest in exploration, feasibility studies and construction of new projects. Global conversion, enrichment and fuel fabrication capacities are more than adequate to meet the demand reflected in both high and low projections of installed nuclear power capacity.

5. Regarding the IAEA Low Enriched Uranium (LEU) Bank, the transit agreement with China entered into force in February 2018, and transport contracts with the authorized organizations from the Russian Federation and Kazakhstan were signed in September and November 2018, respectively. The Agency signed contracts with JSC National Atomic Company "Kazatomprom" and Orano Cycle to purchase LEU.

6. 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. The rest is stored either in reactor pools or in the 151 away-from-reactor spent fuel storage facilities in 27 countries.

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

8. Several countries progressed in their projects on deep geological disposal of high level radioactive waste and/or spent fuel declared as waste. Pioneering borehole disposal projects for disused sealed radioactive sources have reached milestones in Ghana and Malaysia. Disposal facilities for all other radioactive waste categories are operational worldwide.

9. Progress continued to be made in strengthening and improving safety at NPPs and research reactors across the world and numerous peer review missions and advisory services were conducted by the Agency across all safety areas. Member States continued to seek Agency assistance in areas such as

ageing management, management of internal and external hazards, contamination control, use of operating experience, regulatory framework for a nuclear power programme and small and medium sized or modular reactors, as well as decommissioning and radioactive waste management.

10. Several nuclear data libraries, which are essential for all research and development activities in both power and non-power applications, were released in 2018. The International Nuclear Data Evaluation Network (INDEN) was launched to stimulate advances in the neutron cross section evaluations of nuclides that are particularly relevant to nuclear technologies.

11. Novel technologies and instrumentation involving accelerators and ion beams reported encouraging results in areas such as secure communications, material damage simulation, monitoring air pollution, mitigation of the impact of nitrogen oxides and sulphur oxides on climate change and environmental pollution, and measuring surface contamination.

12. The 252 research reactors in operation in 55 countries continue to play an important role in supporting medical, industrial, educational and nuclear power sectors. New research reactors are under construction in seven countries, while several others are planning or considering building new ones. To date, 99 research reactors and 4 medical isotope production facilities have been converted from the use of high enriched uranium (HEU) to LEU or confirmed as being shut down. In 2018, Nigeria's miniature neutron source reactor was converted from HEU to LEU fuel, and the irradiated HEU fuel was returned to China. Nuclear medicine solutions provider Curium completed the conversion of its target manufacturing to be solely from LEU, leading to approximately 75% of the molybdenum-99 sold in the world today being produced without the use of HEU. Although brief outages at some global molybdenum-99 target irradiation facilities and processors in 2018 resulted in some regional supply shortages, efforts by both producers and health practitioners compensated for some of the production fluctuations.

13. Muon radiography is an emerging technique and uses naturally occurring background radiation in the form of cosmic ray muons. Cosmic muons are approximately 10 000 times as energetic as a typical X-ray and as such can penetrate even large structures while leaving no radiation dose beyond natural background levels. Muon radiography imaging techniques can be used as a non-destructive tool for studying the integrity of full-scale civil structures, such as buildings, bridges and tunnels. The techniques can also be applied to geoscience and archaeology, as well as nuclear safety and security and radioactive waste management.

14. Millions of women are screened for breast cancer with low-dose X-ray mammography every year. It is essential to deliver the lowest possible dose while ensuring the best possible image quality for all breast sizes and compositions. Modern mammography units employ a wide range of beam energies to achieve this. Secondary standards dosimetry laboratories help hospitals ensure that their doses are traceable to agreed international standards. Dosimetry equipment needs to be calibrated regularly. High quality ionization chambers that demonstrate a constant response over the range of different beam energies found in clinics are recommended for accurate dosimetry.

15. Radio-guided surgery in gynaecological cancers can decrease short term and long term morbidity when compared to complete lymph node dissection. Sentinel lymph nodes are key to the metastasis process and their mapping and biopsy are therefore central to many cancer treatments. Sentinel lymph node biopsy is considered to be the only reliable method for screening lymph nodes at the micro-metastatic stage. The most relevant advancement in radio-guided surgery related to gynaecological cancer is the introduction into the operation theatre of instruments such as portable gamma-cameras.

16. Food irradiation is an important part of the post-production process, ensuring food free from microbes that cause food poisoning, pests or spoilage organisms, thereby increasing its shelf life.

Traditionally, food irradiation is often outsourced to large separate facilities, but the development of new irradiators and associated technologies are paving the way for a new approach. Technology is shrinking the size of electron beam and X-ray generators and recent developments in machine-source irradiation indicate that irradiation units may be more easily installed on food-packing lines in future.

17. Serious crop losses resulting from climate change call for innovative breeding pipelines to ensure global food security. The combination of plant mutation breeding, marker-assisted selection and high-throughput phenotyping constitutes a powerful recipe for rapid plant adaptation to climate change. Workflow processes are being put in place for cost-effective identification of induced mutations that cause specific phenotypes, and these technologies and methodologies are increasingly flowing to Member States.

18. By 2050 the global demand for animal-origin food is projected to increase by 60–70%. To meet such demand, the livestock industry will require technology-based intensification of its production systems. Access to feed and forage supplies and good pasture will need to be doubled. The innovative application of isotopic and nuclear technology can help build a dataset on feed intake, diet selection and the nutrient content of grasses that livestock feed on, guiding appropriate feeding and grazing management strategies. Micro-nutritional studies can provide the base for mineral supplementation necessary to maximise the health and productivity of animals.

Nuclear Technology Review 2019

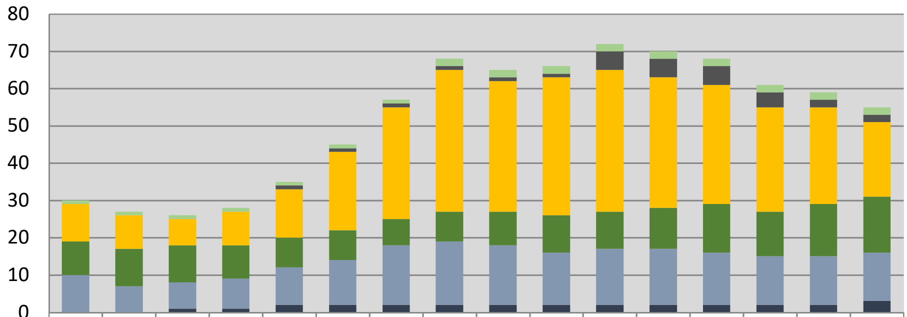
Main Report

A. Power Applications

A.1. Nuclear Power Today

1. As of 31 December 2018, there were 450 operational nuclear power reactors worldwide, with a total capacity of 396.4 GW(e)[1] (see Table A-1), the highest figure to date. This represents an increase of some 5 GW(e) in total capacity, compared to 2017. Of the operational reactors, 82.2% are light water moderated and cooled, 10.9% are heavy water moderated and cooled, 3.1% 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 376 light water reactors.

2. In 2018, nine new pressurized water reactors (PWRs) were connected to the grid: seven in China (Haiyang-1, Haiyang-2, Sanmen-1, Sanmen-2, Taishan-1, Tianwan-4, and Yangjiang-5), and two in the Russian Federation (Leningrad 2-1 and Rostov-4). Seven reactors were permanently shut down: Chinshan-1 in Taiwan, China; Ikata-2, Ohi-1 Ohi-2 and Onagawa-1 in Japan; Leningrad-1 in the Russian Federation; and Oyster Creek in the United States of America).



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
America - Latin	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2
America - Northern	0	0	0	0	1	1	1	1	1	1	5	5	5	4	2	2
Asia - Far East	10	9	7	9	13	21	30	38	35	37	38	35	32	28	26	20
Asia - Middle East and South	9	10	10	9	8	8	7	8	9	10	10	11	13	12	14	15
Europe - Central and Eastern	10	7	7	8	10	12	16	17	16	14	15	15	14	13	13	13
Europe - Western	0	0	1	1	2	2	2	2	2	2	2	2	2	2	2	3

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

3. As of 31 December 2018, 55 reactors were under construction. Construction started on Akkuyu-1 (Turkey), Kursk 2-1 (Russian Federation), Rooppur-2 (Bangladesh), Shin-Kori-6 (Republic of Korea) and Hinkley Point C-1 (United Kingdom). Expansion, as well as near and long term growth prospects,

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

remains centred in Asia (Figure A-1), where 35 reactors are under construction. Asia is also home to 58 of the 68 new reactors that have been connected to the grid since 2005.

Table A-1. Nuclear power reactors in operation and under construction in the world (as of 31 December 2018)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2018		Total Operating Experience through 2018	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	3	1 633	1	25	6.5	4.7	85	2
ARMENIA	1	375			1.9	25.6	44	8
BANGLADESH			2	2160				
BELARUS			2	2 220				
BELGIUM	7	5 918			27.3	39.0	296	7
BRAZIL	2	1 884	1	1 340	14.8	2.7	55	3
BULGARIA	2	1 966			15.4	34.7	165	3
CANADA	19	13 554			94.4	14.9	750	6
CHINA	46	42858	11	10982	277.1	4.2	322	11
CZECH REPUBLIC	6	3 932			28.3	34.5	164	10
FINLAND	4	2 784	1	1 600	21.9	32.4	159	4
FRANCE	58	63 130	1	1 630	395.9	71.7	2 222	4
GERMANY	7	9 515			71.9	11.7	839	7
HUNGARY	4	1 902			14.9	50.6	134	2
INDIA	22	6 255	7	4 824	35.4	3.1	504	11
IRAN, ISLAMIC REPUBLIC OF	1	915			6.3	2.1	7	4
JAPAN	38	36 476	2	2 653	49.3	6.2	1 863	2
KOREA, REPUBLIC OF	24	22 444	5	6700	127.1	23.7	547	5
MEXICO	2	1 552			13.2	5.3	53	11
NETHERLANDS	1	482			3.3	3.1	74	0
PAKISTAN	5	1 318	2	2 028	9.3	6.8	77	5
ROMANIA	2	1 300			10.5	17.2	33	11
RUSSIAN FEDERATION	36	27 252	6	4573	191.3	17.9	1 298	6
SLOVAKIA	4	1 814	2	880	13.8	55.0	168	7
SLOVENIA	1	688			5.5	35.9	37	3
SOUTH AFRICA	2	1 860			10.6	4.7	68	3
SPAIN	7	7 121			53.4	20.4	336	1
SWEDEN	8	8 613			65.9	40.3	459	0
SWITZERLAND	5	3 333			24.5	37.7	219	11
TURKEY			1	1 114				
UKRAINE	15	13 107	2	2 070	79.5	53.0	503	6
UNITED ARAB EMIRATES			4	5 380				
UNITED KINGDOM	15	8 923	1	1 630	59.1	17.7	1 604	7
UNITED STATES OF AMERICA	98	99 061	2	2 234	808.0	19.3	4 408	6
Total [b,c]	450	396 413	55	56 643	2563.0		17 880	11

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

b. Note: The total figures include the following data from Taiwan, China; 5 units, 4448 MW(e) in operation; 2 units, 2600 MW(e) under construction; 26.7 TW·h of nuclear electricity generation, representing 11.4% of the total electricity generated.

c. The total operating experience also includes shutdown plants in Italy (80 years, 8 months), Kazakhstan (25 years, 10 months), Lithuania (43 years, 6 months) and shutdown and operational plants in Taiwan, China (224 years, 1 month).

A.1.1. Operating Countries

4. At the end of 2018, 66% of the 450 operating nuclear power reactors had been in operation for over 30 years. Long term operation and ageing management programmes are being implemented for an increasing number of NPPs.

5. Hungary has nearly completed extending the operating lifetime of its reactors. Four Paks units were approved by the Hungarian Atomic Energy Authority to operate for 20 years beyond their original 30-year licences. Construction of two additional units at Paks (a project referred to as Paks-II) is planned to start in 2020, with commercial operation expected in 2026 and 2027.

6. In May 2018, the Islamic Republic of Iran began soil stabilization work on the construction site of the planned 1050-MW(e) Bushehr-2 unit, which is the first of two planned units. Bushehr-2 and -3 are expected to be connected to the grid in 2026 and 2027, respectively.

7. In Canada, refurbishment works started at Unit 2 of Darlington NPP. Aimed at enabling the station to continue operations until 2055, the refurbishment of all four CANDU units are scheduled for completion by 2026. In August 2018, Pickering NPP was granted a ten-year operating licence, which includes three stages: continued commercial operation until 2024; stabilization activities, such as post shutdown defuelling and dewatering; and safe storage with surveillance

8. Committed to delivering new nuclear capacity under its Clean Growth Strategy of 2017, the British Government has taken action to encourage nuclear new build, with the industry proposing up to 17.8 GW(e) of new build capacity. Site preparation work is under way for the first reactor at Hinkley Point C, which is scheduled to come online in 2025.

9. In July 2018, the Kozloduy plant in Bulgaria completed an upgrade which could extend its lifespan until 2051. In June 2018, the cabinet annulled a 2012 decision that terminated the construction of the Belene NPP, allowing for revival of the project and work at the site.

10. In 2018, studies were under way in Mexico to expand the installed capacity of the Laguna Verde NPP.

11. In July 2018, Armenia confirmed it is working to extend the operating life of Unit 2 at its Metsamor NPP.

12. Romania plans to further increase nuclear generating capacity through the construction and commissioning of Units 3 and 4 at the Cernavodă NPP. In May 2018, it was decided that Cernavodă-1 unit would be shut down for refurbishment in 2026.

13. In August 2018, South Africa released its latest Integrated Resource Plan/National Development Plan, which does not project growth in its nuclear energy capacity before 2030.

14. In May 2018, Czech utility ČEZ carried out a study showcasing no fundamental safety or technical obstacles to a 60-year operating lifetime for units at the Temelin NPP. Also in May 2018, the Government postponed a decision on building new nuclear units.

15. In Belgium, nuclear power plants are intended to be phased out by 2025. As confirmed by the new energy strategy approved by the Government in March 2018, the Doel-3 reactor will be offline by 2022, Tihange-2 by 2023, and the remaining units will be shut down in 2025. The Integrated National Energy and Climate Plan 2021–2030, under development in Spain, is expected to establish the evolution of nuclear energy in the country's energy mix, including a timetable for the closure of NPPs. Germany continues to pursue a nuclear phase-out. Sweden and Switzerland maintain their current nuclear power fleets as scheduled.

16. The operational safety of NPPs remains high, as shown by safety indicators collected by the Agency. Figure A-2 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 the several commonly used safety performance indicators.

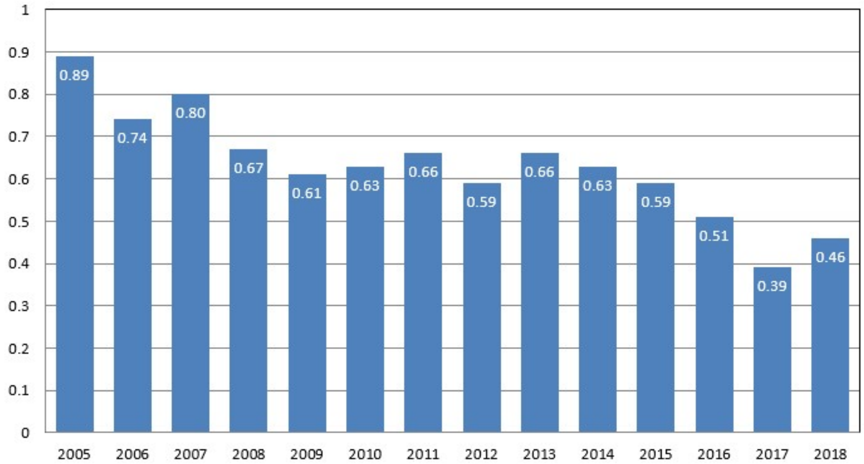


FIG. A-2. Mean rate of scrams: the number of automatic and manual scrams per 7000 hours of operation of a unit. (Source: IAEA Power Reactor Information System www.iaea.org/pris*)*

A.1.2. Expanding Countries

17. Of the 30 operating Member States, 11 are actively constructing additional nuclear power units or expanding their nuclear power programmes. Of the 55 reactor projects under way, 46 are in countries with existing nuclear power programmes, led by China (11), India (7) and the Russian Federation (6).

18. At present, China has 46 operational nuclear reactor units and 11 under construction. In 2018, seven units (Sanmen-1 and -2, Taishan-1, Haiyang-1 and -2, Yangjiang-5 and Tianwan-4) joined the grid. China's energy regulator National Energy Administration is expected to set the nuclear capacity target for 2030 at between 120 and 150 GW(e). China also plans to build 30 reactors overseas by 2030.

19. The Russian Federation has 37 nuclear power reactors in operation and 6 under construction. The latest Russian Federal Target Programme envisages a 25–30% nuclear share in electricity supply by 2030, rising to 45–50% in 2050 and 70–80% by the end of the century. In April 2018, Russia completed building a floating nuclear power plant, the Akademik Lomonosov, which is expected to go into service in 2019.

20. The Olkiluoto-3 EPR project in Finland has moved to the commissioning phase, completing cold and hot functional tests. Commercial operation is planned to start in late 2019. Finland has four nuclear power units in operation and is planning to expand its programme. The operating licences of Olkiluoto-1 and -2 were extended, permitting operation of the two units through 2038. The Hanhikivi-1 project remains under licensing review, with plans to start construction in 2019.

21. The Energy Security Plan in Pakistan set a target of 8800 MW(e) of nuclear power generation capacity by 2030, including a 1100 MW(e) PWR, where construction start is expected in 2020 and commercial operation in 2025.

22. The United States of America has 98 operating commercial nuclear reactors. Construction of AP1000 type Units 3 and 4 at Plant Vogtle, in the state of Georgia, is ongoing, with operations planned to start in 2021 and 2022. In July 2018, it was announced that the single-unit Duane Arnold Energy Center in Iowa will be permanently shut down in late 2020, five years before the expiration of its

operating licence. Operators have filed applications to extend the operation of Turkey Point Units 3 and 4 in Florida, Peach Bottom Units 2 and 3 in Pennsylvania and Surry Units 1 and 2 in Virginia from 60 to 80 years. The USA is the first country to consider extending the lifespan of a plant to 80 years. The single unit Oyster Creek NPP ceased operations in September 2018 after nearly 49 years of commercial operation.

23. In Argentina, the Embalse unit is undergoing a life extension and revamping process. Start-up commissioning of the 30 MW(e) Carem-25 SMR is planned for 2022. In April 2018, the nuclear regulator extended the operating licence of Atucha-1, allowing operation until 2024.

24. In March 2018, the Nuclear Power Corporation of India Limited (NPCIL), from India, and Électricité de France (EDF), from France, signed an agreement on the construction of the Jaitapur NPP, comprising six EPR reactors. In October, India and the Russian Federation signed an agreement for a six VVER unit plant at a yet to be chosen site.

25. The Government of Brazil seeks to increase its nuclear power production, with plans for four new PWRs to be operational in 2025–2030. Construction of the 1405 MW(e) Angra-3 had restarted in 2010, with an initial planned start date of 2018. However, progress is stalled at about 60% completion of the unit, and Electronuclear is pursuing a partnership based model to restart construction. In May, an Agency peer review mission found that Eletronuclear, the state-run operator of Angra-1, made progress in ageing management and preparedness for the long term operation of the reactor.

26. France maintains 58 operational nuclear power units, and a new unit at Flamanville NPP is planned to have fuel loaded by the end of 2019. According to the French Government, the development strategy for nuclear power is related to the goals set forth by the Energy Transition for Green Growth Act and the multiyear energy plan, which is planned to be adopted by mid-2019. The draft plan sets 2035 as the deadline for decreasing the nuclear share in the country's electricity mix to 50%. To reach this target, 14 existing reactors will be shut down by 2035. The Government will work with the nuclear industry to draw up, by 2021, a work plan that will serve as the basis for a decision on the construction of new nuclear power reactors.

27. According to the 8th Basic Plan of Long-term Electricity Supply and Demand of December 2017, the Republic of Korea will continue to pursue the construction of five APR-1400 units before 2023. However, construction of other new units and extensions to the operating lifetimes of existing plants will not be pursued. In June 2018, the operator Korea Hydro & Nuclear Power Company decided to shut down the country's second oldest nuclear reactor, Wolsong-1, based on an economic analysis following the Government's energy transition policy. The reactor had been offline since May 2017 for planned maintenance.

28. In July 2018, it was announced that Unit 3 at Slovakia's Mochovce NPP is expected to be operational in the second quarter of 2019.

29. In July 2018, the operating licence of Rovno-3 in Ukraine was extended by 20 years, so the plant may continue operations until 2037. A feasibility study to resume construction of Khmelnitski-3 and -4 was completed during 2018. The 'Energy Strategy of Ukraine until 2035' foresees nuclear to have a 50% share in the country's electricity production by 2035.

30. In July 2018, the Japanese Government approved the Basic Energy Plan, which confirmed a nuclear share of around 20–22% by 2030. In June 2018, the Tokyo Electric Power Company announced plans to decommission all units at the Fukushima Daini NPP. In the same month, Genkai-4 restarted under new regulatory standards. In 2018, it was ruled that Ohi-3 and -4 and Tokai-2 would be permitted to continue operations.

A.1.3. Newcomers

31. Among the 28 Member States that are considering, planning or actively working to include nuclear power in their energy mix, 19 have initiated studies on nuclear power infrastructure, 5 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.

32. In the United Arab Emirates (UAE), construction progressed on all 4 reactors of Barakah NPP. Unit 1 is expected to start operation in late 2019/early 2020, with the second unit scheduled a year later. An Integrated Nuclear Infrastructure Review (INIR) mission for Phase 3 was conducted at the request of the UAE in 2018. In Belarus, construction of the first NPP at Ostrovets continued, with commissioning of the first and second units scheduled for 2019 and 2020 respectively. In Bangladesh, the first concrete for the second unit of the Rooppur NPP was poured. Commissioning of Units 1 and 2 is expected in 2024 and 2025 respectively. A second NPP project is also planned. In Turkey, a Statutory Decree enacted new nuclear legislation. Construction of the Akkuyu NPP has started, with commissioning of the first unit anticipated for 2023. In Egypt, a site licence for the four-unit NPP at El Dabaa was under review. Construction is expected to start in 2020, with commissioning of the first unit foreseen in 2026. Egypt requested an INIR Phase 2 mission to be conducted in October 2019.

33. Saudi Arabia foresees the parallel construction of an SMR and two conventional NPPs. The procurement process for the two conventional NPPs is ongoing. Construction of the SMR is expected to start in 2020, and of the first large NPP in 2021, with commissioning of the latter foreseen in 2028. An INIR Phase 2 mission took place in July 2018. In Jordan, a dual-track nuclear power programme is also under development, including the selection of an SMR technology by 2019, with a total capacity ranging from 200 to 600 MW(e) depending on electricity demand, to be deployed in 2027–2028, and the construction of a large PWR with around 1000 MW(e), most likely after 2030. In October 2018, Uzbekistan signed an agreement with the Russian Federation for the construction of its first two-unit NPP with a total capacity of up to 2400 MW(e). Nigeria is planning for four reactors, through a build-own-operate-transfer approach, with the first unit to be in operation in 2027. In Kenya, pending a decision to proceed with a nuclear power programme, commissioning of the first NPP is planned for 2027. A Site and External Events Design mission took place in November 2018. Kenya has requested an INIR follow-up mission to be conducted in August 2019. Kenya recently expressed interest in pursuing the construction of a research reactor prior to constructing a NPP. In Poland, commissioning of the first unit is foreseen in 2030 if the Government decides to proceed with the nuclear power programme.

34. Member States continue to benefit from 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 five INIR missions conducted in 2018 in the Niger, the Philippines, Saudi Arabia, the Sudan and the UAE, the number of INIR missions deployed since their launch in 2009 reached 27 in 20 Member States.

A.2. The Projected Growth of Nuclear Power

35. The Agency's 2018 projections (Figure A-3), prepared in consultation with regional experts and reflecting the latest information on policy and market conditions, suggest that nuclear power may struggle to maintain its current place in the global energy mix. In the low projection to 2030, net installed nuclear electricity generation capacity declines by more than 10% from 392 GW(e) at the end of 2017. In the high case, capacity increases by 30% to 511 GW(e) by 2030. Longer term, capacity in the low case continues to decline for around a decade before rebounding to 2030 levels by 2050, with the nuclear share of global generation capacity declining to 2.8% compared with 5.7% today. In the high case,

installed capacity is projected to reach 748 GW(e) by 2050, representing 5.8% of global generation capacity.

36. The wide range between the low and high projections is due to uncertainty regarding the replacement of the large number of reactors scheduled to be retired around 2030 and beyond, particularly in North America and Europe.

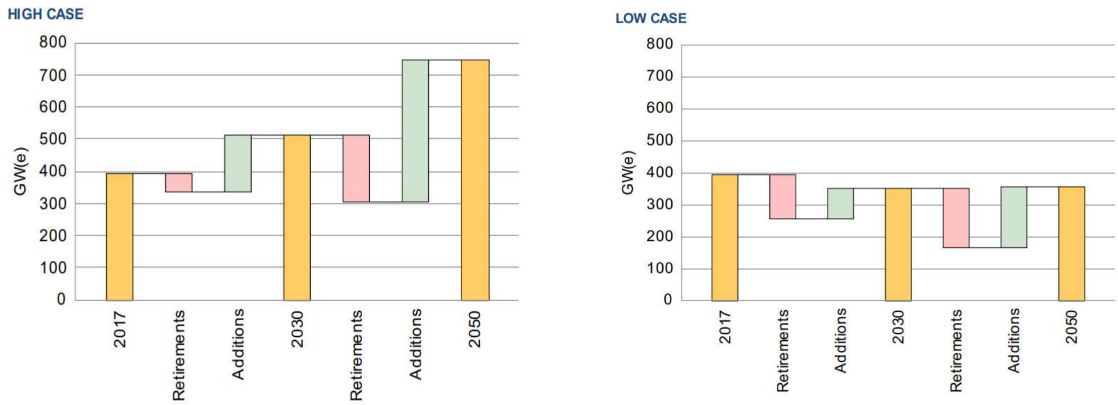


FIG. A-3: High (left) and low (right) projections for world nuclear capacity.
(Source: Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, IAEA Reference Data Series No. 1, 2018)

37. The need to substantially expand the contribution of nuclear power climate change mitigation is reflected in the emissions pathways presented in the recent Intergovernmental Panel on Climate Change special report entitled *Global Warming of 1.5° C*[2]. In most pathways that are consistent with limiting global warming to 1.5°C, nuclear power increases its share by 2050; for example, the four model pathways highlighted in the Summary for Policymakers project an increase in nuclear power generation of at least 59% by 2030 and up to 501% by 2050, relative to 2010.

38. Interest in nuclear power also remains strong in the developing world, particularly in Asia where countries such as China and India are seeking to satisfy rapidly growing electricity demands while reducing GHG emissions. As such, ongoing international climate change negotiations under the United Nations Framework Convention on Climate Change, including the 24th session of the Conference of the Parties (COP24) held in December in Katowice, Poland, represent an important opportunity to highlight the potential role of low carbon nuclear energy in meeting global climate and energy challenges.

[2] IPCC, Global Warming of 1.5°C, 1 October 2018, http://www.ipcc.ch/report/sr15/

A.3. Fuel Cycle

A.3.1. Front End

Uranium resources and production

39. The 26th edition of the biennial joint publication of the OECD Nuclear Energy Agency and the IAEA, *Uranium 2018: Resources, Production and Demand*[3], also known as the 'Red Book', shows that the world's supply of uranium is more than adequate to meet projected requirements for the foreseeable future, regardless of the role that nuclear energy ultimately plays in meeting future electricity demand and global climate objectives. However, the report highlights that significant investment and technical expertise will be required to ensure these uranium resources can be brought into production in a timely manner, including from mines currently under care and maintenance.

40. Uranium spot prices remained relatively depressed in 2018, generally staying within the range of $47/kgU to $59/kgU, slightly higher than the range over 2017, with a generally upward trend over the year. Reduced prices considerably restricted the ability of companies to raise funds for exploration, feasibility studies and new construction projects. 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 or their production was reduced. Thus, world production in 2018 is likely to be similar to that of 2017, which was 59 342 tonnes of uranium (tU), a lower amount than what was reported for 2016.

41. Kazakhstan continued to be the world's leading uranium producer, almost entirely from its in situ leach mines. After rapidly increasing production between 2000 and 2016, production decreased to 23 400 tU in 2017; a similar figure is expected for 2018.

42. In Canada, the second largest producer, the Cigar Lake mine reached full production capacity of 6925 tU in 2017, and a similar amount is expected in 2018. However, suspension of production from the McArthur River mining and Key Lake milling operations, which was announced in November 2017 for a period of ten months, was made indefinite in January 2018 due to continued low demand and low prices for uranium.

43. Namibia's Rössing and Husab mines continued operation over 2018, whereas the Langer Heinrich uranium mine was placed on care and maintenance in May 2018 in response to the prolonged period of low uranium prices. Low-key feasibility work continued at some other Namibian uranium deposits.

44. In Australia, the Four Mile in situ leach uranium mine produced approximately 1500 tU in 2018. At the Ranger project, production is from ore stockpiles only and mining and processing operations are planned to cease by January 2020. In general, work is on hold for several uranium deposits in Western Australia, or some additional studies are being done, but with no firm construction and opening dates.

45. 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.

46. China continued to increase its uranium exploration and development expenditures, both nationally and abroad. In December 2018, China National Uranium Corporation agreed to buy 69% stakes at Rio Tinto's Rössing, the world's longest-operating open pit uranium mine that has produced more uranium than any other mine.

47. The Spanish Nuclear Safety Council continued to analyse the documentation on the Salamanca uranium project in order to issue its compulsory report on the construction authorization for the uranium

[3] Published in December 2018 at https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf

concentrate manufacturing plant. This is one of the approvals required before the plant can begin operation.

48. Feasibility and regulatory work is ongoing at the Engenho mine in Brazil's Bahia state for another open pit operation, near the exhausted Cachoeira mine.

Conversion and enrichment

49. Current conversion and enrichment capacity is more than sufficient to meet the global demand, albeit with a segmented market and production centred on a few suppliers.

50. In September 2018, Orano inaugurated at Tricastin, France, its new conversion plant as part of the Comurhex II project. Designed with the most advanced technologies, the 'Philippe Coste' plant has very low levels of chemical and energy consumption. Three flame furnaces will produce up to 15°000 tonnes of uranium hexafluoride (UF_6) per year.

51. The main molecular laser process to enrich uranium is SILEX, utilizing UF_6. In June 2018, Australia's Silex Systems decided to abandon its acquisition of a majority stake in Global Laser Enrichment (GLE), a joint venture of General Electric (GE), Hitachi and Cameco. Silex Systems stated that, despite being at an advanced stage of negotiations with GE-Hitachi, there were too many risks associated with GLE's business case.

Fuel fabrication

52. In January 2018, US nuclear fuel technology companies Lightbridge and Framatome Inc. launched Enfission, a 50–50 joint venture company to develop, licence and commercialize nuclear fuel assemblies of Lightbridge's advanced metallic fuel. The fuel is made from a zirconium-uranium alloy and uses a unique composition and fuel rod geometry, which the company says offers improvements to the economics, efficiency and safety of existing and future nuclear power plants.

53. In January 2018, Westinghouse Electric Company announced that it had signed a contract with Energoatom extending its supply of nuclear fuel to VVER reactors in Ukraine from 2020 to 2025.

54. Westinghouse and its eight European consortium partners announced in March 2018 the successful completion of a European Union funded project targeted at diversifying the nuclear fuel supply for Russian designed VVER-440 reactors in Europe.

55. In March 2018, Unit 1 of the Edwin I. Hatch NPP in the USA began lead tests by using Global Nuclear Fuel's (GNF) accident-tolerant fuel assemblies, composed of iron-chromium-aluminium fuel cladding material, known as IronClad, and coated zirconium fuel cladding, known as ARMOR. In May 2018, GENUSA (a joint venture between Spanish ENUSA and GNF) was selected by Swedish utility Vattenfall to provide eight fuel reloads for the Forsmark NPP from 2020 to 2023.

56. In April 2018, Russian nuclear fuel company TVEL (part of the State Atomic Energy Corporation "Rosatom") signed agreements with the Atomic Energy Organization of Iran and the Nuclear Power Production and Development Company to replace fuel assemblies of the UTVS design with TVS-2M fuel cartridges for the VVER-1000 reactor at the Islamic Republic of Iran's Bushehr NPP in 2020. In August, TVEL supplied the first batch of modified TVSA-T.mod.2 nuclear fuel for the VVER-1000 reactor at Temelin NPP in the Czech Republic. At Rostov NPP in the Russian Federation, the VVER-1000 reactor was loaded with an experimental batch of TVS-2M fuel cartridges with an anti-debris filter, developed under the country's 'Zero Failure of Nuclear Fuel' project.

57. In May 2018, ENUSA of Spain and Westinghouse Electric Company signed a framework cooperation agreement to collaborate in the development of Westinghouse's EnCore Accident Tolerant Fuel. The fuel incorporates concepts such as chrome-plated zirconium alloy sheaths, silicon carbide sheaths and uranium silicide (U_3Si_2) fuel pellets.

58. In June 2018, India's Nuclear Fuel Complex announced its intention to expand its fuel and reactor components production facilities in Hyderabad and Kota to meet the demand for the proposed new reactors.

59. In August 2018, Canada's SNC-Lavalin signed an engineering service contract and a licensing agreement with the Third Qinshan Nuclear Power Company for the implementation of a CANDU-6 specific modified 37-element fuel bundle, using natural uranium equivalent (NUE) and natural uranium (NU). The fuel is intended to be used in Units 1 and 2 of the Qinshan Phase III NPP in China's Zhejiang province. This would represent the first commercial use of this modified fuel bundle that uses both NUE and NU.

60. In September 2018, Framatome signed a contract to supply and install chromium-coated fuel rods into Unit 1 of Entergy's Arkansas Nuclear One NPP in late 2019. Vattenfall has also contracted Framatome to supply ten reloads of fuel assemblies manufactured at its facility in Lingen, Germany, between 2021 and 2024, for Forsmark-3 and Ringhals-3 and -4.

61. In October 2018, the US National Nuclear Security Administration issued a contract termination notice to the consortium building the Mixed Oxide (MOX) Fuel Fabrication Facility , also called the MOX Project, at the Savannah River Site, in South Carolina. The facility was intended to dispose of at least 34 tonnes of weapons-grade plutonium by turning it into fuel for commercial nuclear reactors.

62. In December 2018, the first industrial batch of MOX fuel was commercially produced at the Mining and Chemical Complex in Zheleznogorsk, Russian Federation, for the BN-800 fast neutron reactor.

A.3.2. Assurance of Supply

63. 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, Kazakhstan.

64. In 2018, the transit agreement with China entered into force, and transport contracts with the authorized organizations from the Russian Federation and Kazakhstan were signed.

65. The Plan of Specific Activities is nearing completion, having addressed issues including those related to Kazakhstan's regulatory framework, site safety and security.

66. The Agency has signed contracts with Kazatomprom of Kazakhstan and Orano Cycle of France to purchase LEU and aims to have the LEU delivered to the IAEA LEU Storage Facility before the end of 2019.

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

A.3.3. Back End

Spent fuel management

68. To date, over 400 000 tonnes of heavy metal (t HM) have been discharged from NPPs. So far, about 75% of discharged fuel from commercial power reactors are stored either in reactor pools or in away-from-reactor (AFR) dry/wet spent fuel storage facilities. There are currently 151 AFR storage locations in 27 countries.

69. The underground canister based dry storage system at the shutdown San Onofre NPP in the USA received the first transfers of loaded fuel storage canisters in February 2018. The below-ground design

was selected as it presents resistance to extreme seismic events. Also in February 2018, the US Nuclear Regulatory Commission declared its acceptance of the licence application made in March 2017 for the development of a Consolidated Interim Storage Facility in Lea County, New Mexico. The facility is also planned to utilize a below-ground dry storage canister system, initially storing up to 8680 t HM of spent fuel.

70. In July 2018, the Spanish Ministry for Ecological Transition requested the Nuclear Safety Council (CSN) to suspend the issuance of the report on the licence application for the construction of the proposed centralized storage facility for high level waste (HLW) and spent nuclear fuel. The programme of activities to carry out the suspension was approved by the CSN on 25 July 2018.

71. In Japan, work commenced in August 2018 to remove the spent fuel from the Monju prototype fast breeder reactor sodium-filled storage tank. The fuel assemblies are transferred to an onsite storage pool after removing residual sodium.

72. In Borssele NPP in the Netherlands, the first spent MOX fuel was discharged and put into the reactor spent fuel pool in May 2018. It is envisaged that the spent MOX fuel will be stored there for four years before transport. The Netherlands recycling strategy will result in there being no spent fuel for deep geological disposal, as was outlined in the report from the OPERA project, issued in January 2018.

73. In Japan, space is being created in the common spent fuel pool in Fukushima by transferring fuel assemblies to an on-site temporary dry storage facility. The temporary facility has been in operation since April 2013 and has the capacity to store 50 dry storage casks. Operators have been undergoing hands-on training in 2018 to be able to remotely defuel Unit 3's spent fuel pool and store the fuel in the common spent fuel pool.

74. In Germany, ownership of the AFR dry storage facilities will be transferred from the utilities to the state-owned company BGZ as of 1 January 2019.

75. The remaining, approximately 100 000 t HM discharged from the global NPP fleet have been reprocessed. Annual world reprocessing capacity is about 5000 tonnes per year for normal oxide fuels, but currently not all of it is used.

76. With a total annual capacity of 1700 tonnes, Orano's two nuclear fuel reprocessing plants UP2-800 and UP3 of La Hague, France, reprocess on average 1000–1100 t HM per year (over 34 000 tonnes of nuclear spent fuel have been reprocessed since 1976): extracted plutonium is recycled into MOX fuel in the MELOX plant at the Marcoule site. Orano pursued in 2018 the decommissioning of its first-generation UP2-400 plant.

77. Mayak Production Association's RT-1 plant in Ozersk, Russian Federation, reprocessed more than 32 t HM of VVER-1000 spent fuel in 2018, following upgrades made in 2017. In addition, experimental reprocessing of MOX spent fuel from the BN-600 fast reactor was also completed. A licence was granted to operate the first pilot demonstration centre for innovative reprocessing technologies at the Mining and Chemical Complex in Krasnoyarsk, with one VVER-1000 spent fuel assembly having been reprocessed in 2018. A second pilot demonstration centre with 250 t HM/year is under construction and is scheduled for completion in 2020.

78. In January 2018, China and France signed an agreement for the construction of a reprocessing and recycling plant in China. In June, Orano and the China National Nuclear Corporation launched the preparatory works for the plant, which will have a capacity of 800 tU/year.

79. Japan Nuclear Fuel Limited, operator of the Rokkasho Reprocessing Plant, announced in late December 2017 that the completion of the facility had been delayed for three years to enable additional

regulatory requirements to be met, such as ensuring containment and recovery in the event of a severe accident.

80. The Thermal Oxide Reprocessing Plant in the United Kingdom completed its operation in November 2018. During its lifetime, it reprocessed 9300 tU of oxide fuel, including domestic advanced gas reactor fuel, overseas PWR and boiling water reactor fuel, and fuel from UK prototype reactors.

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

A.4.1. Decommissioning of Nuclear Facilities

81. As of 31 December 2018, 173 power reactors have been shut down or are undergoing decommissioning across the world. Of those, 17 reactors have been fully decommissioned, while more are approaching the final stages of decommissioning. More than 150 fuel cycle facilities have been permanently shut down or are undergoing decommissioning and close to 130 have been decommissioned. Over 120 research reactors have been shut down or are undergoing decommissioning and over 440 research reactors have been fully decommissioned.

82. Deployment of proven technologies, and research and development work are delivering continuous improvements, mainly in countries with extensive nuclear power programmes. For example, technical progress has been achieved in the implementation of decontamination and segmentation of primary circuit components at several nuclear power plants in France, Germany, Russian Federation, Slovakia, Spain and Sweden. In June 2018, Italy hosted an IAEA Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (ARTEMIS) mission to review SOGIN's plans for dismantling of the Garigliano and Trino NPP reactor pressure vessels and internal parts. This review was a follow-up of a previous ARTEMIS mission conducted in 2017 with the purpose of reviewing the overall decommissioning plans for all SOGIN sites.

83. Progress on NPP decommissioning projects, supported by the European Bank for Reconstruction and Development, continues in Bulgaria, Lithuania, Slovakia and Ukraine. Examples include the start of operation of a new plasma melting facility for decommissioning waste in Kozloduy NPP, completion of cooling towers demolition in Bohunice NPP and full operation of the Chernobyl Unit 4 New Safe Confinement.

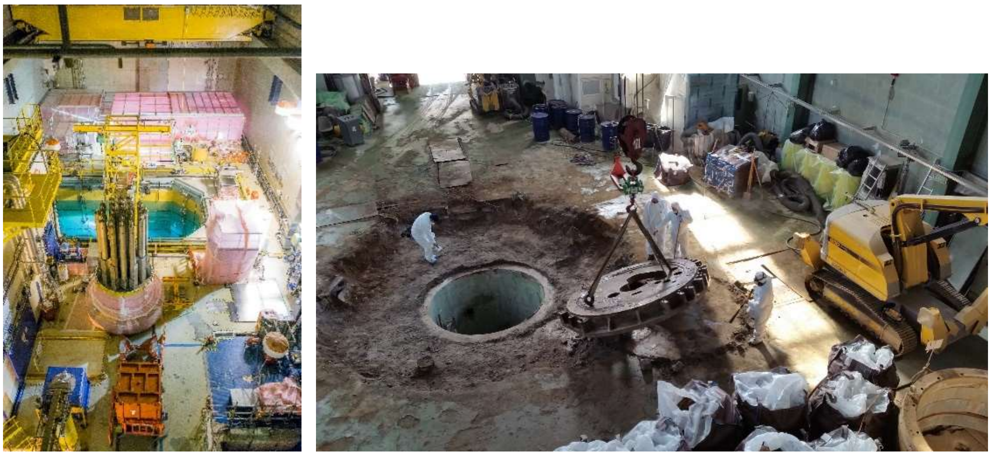


FIG. A-4. Dismantling of Chooz A nuclear power reactor components, France (left), and decommissioning progress at the Magurele research reactor, Romania (right). (Photos: EDF, IAEA)

84. With regard to the decommissioning of research reactors, the dismantling of the biological shield of the 2 MW(th) VVR-S reactor at Magurele near Bucharest, Romania, is currently at an advanced stage of implementation (Figure A-4). The 'FOTON' homogeneous research reactor in Tashkent, Uzbekistan,

has been fully decommissioned, with the reactor site released from regulatory control and now available for alternative industrial uses.

85. In October 2018, Japan's Nuclear Damage Compensation and Decommissioning Facilitation Corporation issued the *Technical Strategic Plan 2018 for Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc*. The work on decommissioning of the Fukushima Daiichi site is progressing, with completion of the land-side impermeable walls (frozen walls) and preparation toward fuel removal from the spent fuel pool in Unit 3.

A.4.2. Remediation

86. Progress has been achieved in 2018 in the preparation of remediation projects for uranium legacies in Central Asia. Funded by the European Commission, the project "Conducting an Integrated Environmental Impact Assessment and Feasibility Study for the Management and Remediation of the Uranium Production Legacy Sites of Degmay and Taboshar in Tajikistan" was completed. Intensive work was performed under a similar European Commission funded project for the uranium production legacy sites of Mailuu Suu, in Kyrgyzstan. Under the Commonwealth of Independent States (CIS) intergovernmental target programme, technically led by the Russian Federation, the Kadji-Sai tailing dump in Kyrgyzstan was made environmentally safe. Large-scale engineering works continued at the Tuyuk-Suu and Dalnee facilities. In November 2018, the CIS Council of Heads of Governments approved funding for remediation activities in Tajikistan, scheduled to start in 2020. International support for the Central Asian countries in remediating their uranium production legacy sites is coordinated by the Coordination Group for Uranium Legacy Sites (CGULS) under joint leadership of the Agency, the European Commission and representatives of the beneficiary countries.

87. Placement of the interim cover on the last big tailings pond at the Culmitzsch site was finished in 2018, within the Wismut Environmental Remediation Project, a large scale project for remediating uranium production legacies in eastern Germany (Figure A-5). With that, all radioactive tailings (178 million cubic metres) are safely covered. Work to place the final cover at the Culmitzsch pond will last until 2028. At some other sites, the federal Government owned company Wismut has been switching to implementation of long term tasks, mainly water treatment and long term surveillance and maintenance of the remediated objects.

FIG. A-5. Culmitzsch tailings pond under remediation, Germany, 2018. (Photo: Wismut GmbH)

88. Progress in off-site decontamination was regularly reported by Japan. In the Intensive Contamination Survey Area, where the air dose rate was measured at over 0.23 μSv/h (equivalent to over 1 mSv/y), all the responsible municipalities have completed planned decontamination activities as of March 2018. All the required full scale decontamination has now been completed, except in the 'difficult-to-return' zones.

A.4.3. Radioactive Waste Management

Management of disused sealed radioactive sources

90. End-of-life management options for disused sealed radioactive sources (DSRSs) were explored further, including co-disposal with other waste at suitable facilities. The number of recycling and repatriation options increased. Borehole disposal projects are at various stages of development in several countries, including Ghana, Malaysia and the Philippines. Implementation of the borehole disposal project in Malaysia is in the final review of the safety case, with drilling to begin in early 2019.

91. A number of successful operations have been conducted in 2018 to remove DSRSs from user premises and bring them under control in proper storage conditions. The removal of all of Brazil’s remaining disused Category 1 and 2 sources was finalized with the shipment of the last batch of sources to the USA. Under this operation, the largest so far using the Mobile Hot Cell, 81 teletherapy sources, with a collective activity of 1093 TBq (29 500 Ci), were either repatriated or sent to a source-recycling company. With funding from Canada, 27 Category 1 and 2 DSRSs were removed from Bolivia, Ecuador, Paraguay, Peru and Uruguay, and transported for recycling. Another 3 Category 1 and 2 DSRSs were also removed from Lebanon. In several other Member States, including Albania, Burkina Faso, Cyprus, Nepal, Tunisia and North Macedonia, the removal of Category 1 and 2 sources has been initiated.

92. The commissioning of the Mobile Tool Kit Facility to be used in conjunction with the borehole disposal system was completed in 2018, with the first implementation planned in Malaysia in early 2019.

93. Operations involving the conditioning of DSRSs were completed in Chile, Cyprus, Ghana, Honduras, Indonesia, Jordan, Malaysia, Slovenia, Sri Lanka and Viet Nam, with local personnel in these countries receiving appropriate training on DSRS conditioning. Institutions in two Member States were subsequently approved and licensed by their national competent authority to perform conditioning operations which will aid other Member States regionally into the future.

94. National inventories of DSRSs, as well as sealed sources in use, were established and/or updated in Antigua and Barbuda, Bahamas, Barbados, Belize, Dominica, Guyana and Papua New Guinea.

95. The International Catalogue of Sealed Radioactive Sources and Devices is accessible to a larger group of users from Member States, facilitating the identification of DSRSs found in the field. Efforts to add more details on sources and devices were initiated in 2018.

Radioactive waste predisposal

96. In February 2018, EDF subsidiary Cyclife began operations for the treatment of 1800 tonnes of radioactively contaminated metal arising from the decommissioning of Trino, Garigliano and Latina nuclear power plants in Italy, following an agreement signed with SOGIN in 2017.

97. Chernobyl NPP is starting to process liquid radioactive waste in a major step toward cleaning up the 1986 nuclear accident, with the operators beginning to transfer much of the facility’s liquid nuclear waste into long term storage. Chernobyl’s liquid radioactive treatment plant will process 22 000 tonnes of contaminated water resulting from the accident as well as from the operation of the plant’s other three reactors. The wastewater treatment plant, which went into operation in January 2018, is expected to remove radioactive contaminants from water at a rate of about 2000 tonnes a year for the next 20 years.

98. A plasma melting facility at Bulgaria's Kozloduy NPP has started operations, facilitating nuclear waste processing to support decommissioning activities. The technology allows for treatment of waste with a minimum risk of radioactive contamination. The final waste form is durable and free from organics and liquids, effectively a chemically inert and amorphous glassy slag. Moreover, historical radioactive waste conditioned in a bituminous or concrete matrix can be re-treated in a plasma facility to produce a waste disposal package complying with the acceptance criteria of the Kozloduy near surface

of contaminated water resulting from the accident as well as from the operation of the plant's other three reactors. The wastewater treatment plant, which went into operation in January 2018, is expected to remove radioactive contaminants from water at a rate of about 2000 tonnes a year for the next 20 years.

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99. A project to demonstrate the use of radioactive waste vitrification technology at the damaged Fukushima Daiichi NPP in Japan was launched in April 2018, comprising two main parts. The first is to develop and study durable waste form conditioning matrix formulations. Tests on a laboratory scale (100 g), bench scale (1 kg) and near-industrial scale (100 kg) will be carried out at the French Alternative Energies and Atomic Energy Commission's Marcoule laboratories. The second part of the project is to conduct feasibility studies for process implementation, operation and maintenance principles and waste disposal.

100. The first transfer of radioactive liquid waste from an underground waste tank to a 'mega-volume' facility — Saltstone Disposal Unit (SDU) 6 — has been completed at the US Department of Energy's Savannah River Site. SDUs are designed to contain low activity waste grout produced from the solidification of decontaminated non-hazardous salt waste at the South Carolina site. The cylindrical concrete tanks are based on a design used commercially for the storage of water and other liquids. SDU 6, which was completed last year, is the site's first mega-volume SDU and is more than ten times larger than other existing SDUs at the site. The SDU 6 is about 114 metres in diameter and almost 13 metres high. In total, seven such mega-volume units are planned to meet disposal needs at the site.

Radioactive waste disposal

101. Disposal facilities for all categories of radioactive waste, 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) or for low level waste (LLW) in arid areas (e.g. South Africa, USA); near surface engineered facilities for LLW (e.g. China, Czech Republic, France, Hungary, India, Japan, Poland, Russian Federation, Slovakia, Spain, United Kingdom); and engineered facilities for low and intermediate level waste (LILW) sited in geological formations at a range of depths (e.g. Czech Republic, Finland, Germany, Hungary, Republic of Korea, Norway, Russian Federation).

102. Further disposal facilities for LILW, including in Belgium (Dessel), Bulgaria (Kozloduy-Radiana), Canada (Kincardine), Germany (Konrad), the Islamic Republic of Iran (Talmesi), Lithuania (Stabatiškės), Romania (Saligny) and Slovenia (Vrbina), as well as a disposal facility for LLW in Canada (Chalk River), are at different stages of licensing or construction.

103. Disposal options for naturally occurring radioactive material waste vary according to national regulations and range from trench disposal facilities to subsurface engineered facilities, such as in Norway.

104. Bulgaria's Radioactive Waste State Enterprise is continuing constructing of a near surface disposal facility for LLW at the Radiana site, near the Kozloduy NPP.

105. In the Islamic Republic of Iran, construction of the Talmesi near surface disposal facility continues, and waste containers were accepted for on-site storage, pending the start of disposal operations.

106. In Finland, the waste management company Posiva is conducting a full-scale in-situ system test, a condition for obtaining an operating licence for the repository under construction at Olkiluoto. The test is intended to demonstrate the full system design needed to place nuclear fuel assemblies packed in the copper-steel canisters in deposition holes drilled into the granitic host rocks in specially constructed deposition tunnels. The test includes backfilling of the deposition tunnels with bentonite clay and installation of the final reinforced concrete plug sealing system. The test will utilize two full-scale canisters outfitted with heating elements to simulate the residual heat expected from the used fuel.

107. In January 2018, authorities in Sweden issued rulings affecting the licensing process for the Swedish spent fuel disposal facility proposed by SKB. The Swedish Radiation Safety Authority supported the construction of the final disposal facility in Forsmark, saying that SKB has the required capabilities for safe implementation of final disposal. The Land and Environmental Court statement said SKB's application for the most part met the requirements for approval, but that there were still some uncertainties related to the long term performance of the copper canister as far as the corrosion processes of copper are concerned. SKB is responding to this request for further information.

108. The management solution adopted in France for high level or intermediate level long lived radioactive waste (HLW/ILW-LL) is deep geological disposal in Callovo-Oxfordian claystone. The Andra Cigéo project is aimed at implementing this decision as enshrined in a law adopted in 2006. Andra is finalizing the detailed design phase and is working on baseline optimizations. Following a technical examination phase on the safety options file, the French Nuclear Safety Authority (ASN) consulted the public in 2017 about its draft opinion. After analysing the contributions received, ASN issued its opinion in January 2018, saying that the project has on the whole achieved sufficient technical maturity at the safety options file stage. However, supplemental information on justification for the disposal facility architecture, the design and sizing of the installation to withstand natural hazards, the monitoring of the facility, the prevention of potential fire ignition of tar-based waste canisters, and the management of post-accident situations are requested for the construction authorization application that Andra intends to submit in 2019 or early 2020.

109. In November 2018, the Swiss Federal Council announced its decision on Stage II of the Sectoral Plan for Deep Geologic Repositories. This allows Nagra, the Swiss radioactive waste management organization, to focus further detailed site characterization on the remaining three potential siting regions. It effectively initiates the third and the last phase aimed at submitting a licence application for a geological disposal facility by 2024.

110. In December 2018, the UK Government published its policy on Working with Communities, as part of the launch for a national, consent-based siting for a geological disposal facility.

B. Atomic and Nuclear Data

111. Nuclear data libraries that are essential for all research and development activities in nuclear applications — both power and non-power — are released by several agencies, in addition to data hosted by the Agency.[4] The most important releases in 2018 were as follows:

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[4] Available at https://www-nds.iaea.org.

- The ENDF/B-VIII nuclear data library, released by the USA, has major changes for neutron reactions on the most important nuclides for nuclear applications, notably the major uranium isotopes, iron, oxygen and hydrogen. A major effort has gone into evaluating new measurements for fission-related quantities for actinides, such as the prompt fission neutron spectrum and average number of fission neutrons. ENDF/B-VIII has been validated extensively, especially for criticality benchmarks.
- The JEFF-3.3 nuclear data library, released by the OECD/NEA, is expected to be mostly used in European reactor analyses, reactor software, fuel cycle analyses and fusion.
- A new Photonuclear Data File, JENDL/PD-2016, released by Japan, provides the data of photon-induced nuclear reactions, such as photoabsorption, photofission, particle and residual-nuclide production cross sections, and double-differential cross sections of emitted particles. The library contains data for 2681 nuclides with an energy range of incident photon from 1 MeV to 140 MeV.
- JENDL/AD-2017, the Activation Cross Section File for Nuclear Decommissioning, also from Japan, is aimed at meeting the needs of radioactive inventory evaluation during decommissioning of nuclear facilities.
- A new release of the TALYS-based Evaluated Nuclear Data Library, TENDL-2017[5] succeeds TENDL-2015. The collection contains complete ENDF-6 formatted data files, including covariance data, up to 200 MeV of incident energy, for 2813 isotopes (all stable or with a half-life greater than 1 second) for incident neutrons, photons, protons, deuterons, tritons, helium-3 and alpha particles.

112. The data on total absorption gamma-ray spectroscopy (TAGS) would be an important addition to existing decay data libraries, as they could have an impact on decay heat and anti-neutrino spectra calculations. It is therefore important to review the current status of TAGS and discuss new data requirements. A detailed assessment of the decay data of the main fission product contributors to decay heat for a wide range of fuel systems, which has led to updated priority tables for total absorption and high resolution gamma ray spectroscopy measurements, was completed by the Agency in 2018, and will be published in 2019.

113. The International Nuclear Data Evaluation Network (INDEN) was launched in 2018 to stimulate advances in the neutron cross section evaluations of nuclides that are particularly relevant to nuclear technologies (Figure B-1). Nuclear physics experts will coordinate their efforts in innovative measurements and model simulations to come to the best possible nuclear reaction data tables for light nuclides such as those of carbon and nitrogen, structural materials such as chromium and nickel, and important actinides such as the plutonium isotopes. Apart from fundamental nuclear data improvements, updates in nuclear data libraries will be directly validated through integral criticality benchmarks for both thermal and fast neutron energies. Experts contributing to this development come mostly from China, European countries, Japan, and the USA, with the Agency playing a coordinating role.

[5] Available at https://tendl.web.psi.ch/tendl_2017/tendl2017.html.

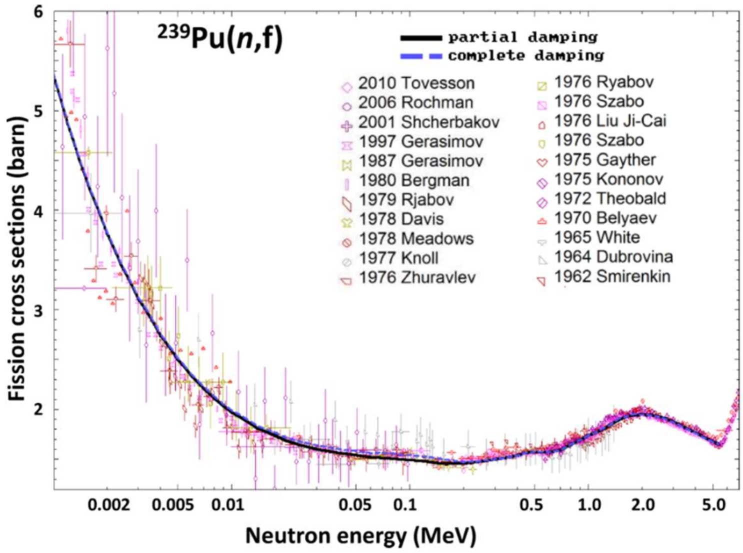

FIG. B-1. Current status of fission cross sections for U-235 as under study in the INDEN collaboration.

C. Accelerator and Research Reactor Applications

C.1. Accelerators and Associated Instrumentation

C.1.1. Breakthrough Technologies with Ion Beam Engineering

114. Thanks to the most recent developments in accelerator technology, it is possible to create optically active, atom-sized defects in a vast class of materials, ranging from wide-bandgap semiconductors (e.g. diamond, silicon carbide, gallium nitride) to two-dimensional materials (e.g. hexagonal boron nitride) (Figure C-1). These systems represent a promising platform in single photon emission, an emerging field with applications in secure communication (safe key distribution with single photon states) and cellular labelling/sensing. Several ion implantation strategies are currently under development within the framework of a collaborative international effort with support from the Agency. In the near future, ground-breaking innovation can be foreseen both in quantum-secure communication and biotechnology.

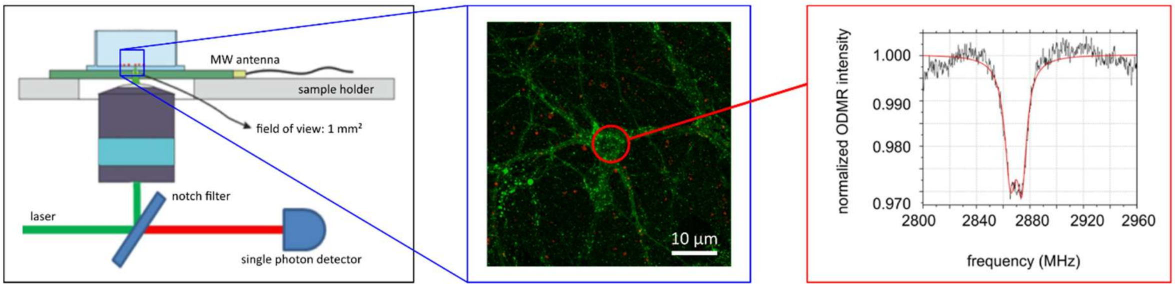

FIG C-1. Application of ion beams for the creation of luminescent nanodiamonds internalized in living neuronal cells in culture: (left) schematics of the experimental setup for imaging and signal acquisition; (centre) confocal microscopy map highlighting internalized luminescent nanodiamonds; (right) optically detected magnetic resonance from nanodiamonds. (Courtesy of Paolo Olivero, University of Torino, Italian National Institute of Nuclear Physics and Italian National Institute of Metrologic Research)

C.1.2. Simulating Reactor Materials Damage with Accelerators

115. Ion beams, when properly selected and tuned, are able to model experimentally the material damage induced by thermal and fast neutrons present in fission or fusion reactors. As there is currently no fusion neutron dedicated source with a high enough flux to mimic irradiation conditions relevant to those experienced by the first wall in a fusion reactor, ion beam accelerators are used as an alternative to reproduce as far as possible microstructural changes as well as the composition of the materials for detailed microstructural characterization studies. For example, one to three electrostatic accelerators in the range from a few hundred kV to a few MV can be coupled to operate in single-, dual- or triple-beam configuration to create ballistic damage and simultaneously implant relevant transmutation elements such as helium and hydrogen, which are the main neutron induced reaction products in structural materials.

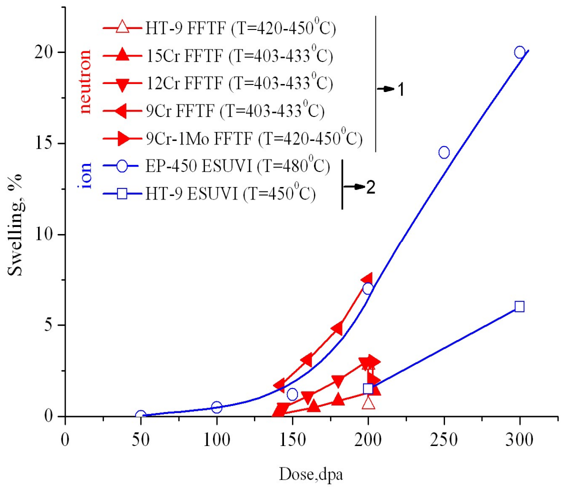

FIG. C-2. Comparison of materials swelling due to fast neutron (in red) and ion beam (in blue) irradiations, presented as a function of different damage doses (dpa: displacements per atom). (Courtesy of V. Voyevodin, Kharkov Institute of Physics and Technology)

116. However, before such an approach can be fully qualified, international efforts and coordination are required in the form of a standardized exercise able to determine the reproducibility of results at different sites, best practice guidelines for accelerators, and the degree to which ion beam irradiation may be used for fast screening of future nuclear structural materials. In this context, the Agency

coordinates[6] a worldwide round robin irradiation experiment to compare damage microstructures of T91 steel among ion beam accelerators, as well as between ion beam accelerators and an irradiation of the same material in the BOR-60 fast research reactor in the Russian Federation.

C.1.3. Large Scale Air Pollution Monitoring Using Nuclear Analytical Techniques

117. Air pollution is a worldwide problem that can affect the environment and human health, and air quality management plays an important role in reducing the level of emissions. However, there is a lack of data to support the identification of sources of pollution affecting the population of major cities, as well as to clarify the pathways of its transboundary transport. In order to develop better mitigation strategies and tools, Member States, with support from the Agency, are using nuclear analytical techniques and other complementary methods to determine the elemental composition of airborne particulate matter (Figure C-3). Such information serves to identify the major sources of pollution (source apportionment) and their specific contribution to the observed pollution (inventory). Several techniques have the advantages of multi-elemental capability, being non-destructive (thus allowing to preserve the samples for further analysis) and speed in obtaining information of around twenty chemical elements relevant for source identification. Among these techniques, ion beam analysis, X-ray fluorescence spectrometry (XRF) and neutron activation analysis are the most employed.

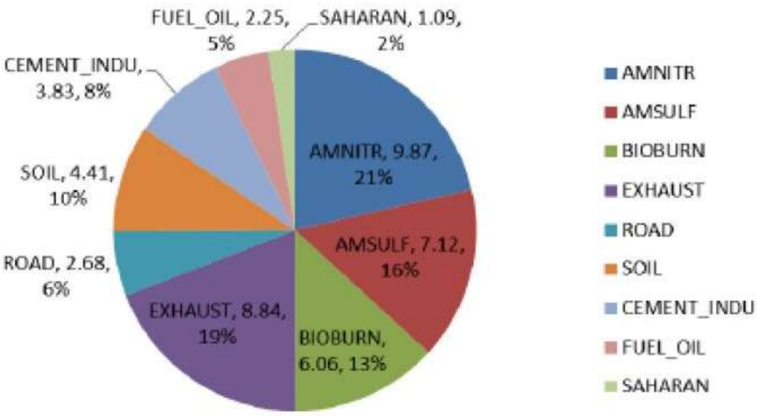

FIG. C-3. Example of relative contribution of pollution sources (inventory), based on elemental analysis of samples using various nuclear techniques. (Source: IAEA)

118. The increased interest and importance of the subject was also reflected during the Agency's proficiency test exercise using samples from urban dust loaded on air filters, where more than 40 analytical laboratories from 33 Member States participated and submitted their results as part of their quality assurance and control procedures.

C.1.4. Field Measurements for Characterization of Surface Contamination

119. Uranium mining and milling is an intensive industry that has left a legacy in many countries of radiologically affected sites that were subject to regulatory control not in accordance with current international standards. The exploitation of other mineral resources, including oil, also led to significant accumulation of naturally occurring radioactive materials. Other sites were contaminated as a result of nuclear and/or radiological accidents, as well as nuclear weapons testing. For example, tailing repositories alone account more than 50 sites and the volume of tailings and waste rocks exceeds 800 million tonnes in the Central Asia region alone. These sites could in principle lead to the exposure of members of the public to ionizing radiation resulting in negative health effects.

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[6] Built on the previous IAEA coordinated research project, entitled *Accelerator Simulation and Theoretical Modelling of Radiation Effects in Structural Materials*, with results published in 2018.

120. The state-of-the-art in portable instrumentation, the free access to geographic information systems and the development of geostatistics modelling tools offer multiple choices to implement in-situ surveys for a variety of environmental scenarios and compartments. In-situ techniques have reached a high level of analytical performance and offer many advantages over other more traditional techniques, including fast determination of contaminant concentrations/activities, identification of hot spots, cost reduction for the investigations, and fast determination of the contaminant's spatial distribution. In-situ measurements can also improve the sampling strategies for high accuracy laboratory analysis if needed.

121. Upon request from Member States, Agency activities in 2018 in this area included: a field demonstration of radiological mapping in support of the release of the FOTON Radiation and Technology Complex site in Uzbekistan after radioactive waste disposal; a demonstration of capabilities of drone based radiological mapping systems for site measurements in case of a nuclear emergency in Brazil; and support to a national training course on radiological measurements, in situ techniques and methodologies in Mexico (Figure C-4).

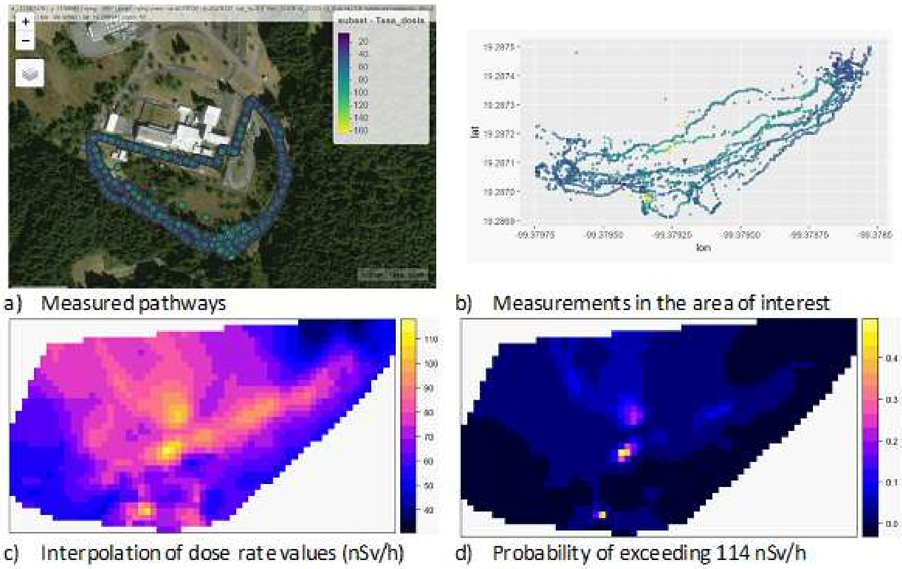

FIG. C-4. Example of the results of a field measurement exercise conducted as part of a national training course under TC project MEX7011. The measurement pathways are represented in maps, including interpolation of dose rates over the surveyed area as well as probability estimates for exceeding a given level. (Source: IAEA)

C.2. Research Reactors

122. The most frequent applications for research reactors are shown in Table C-1. Their power can range from zero (e.g. critical or subcritical assemblies) to approximately 200 MW(th). There is much greater design diversity for research reactors than for power reactors, and they also have different operating modes, which may be steady or pulsed.

Table C-1. Common applications of research reactors around the world[7].

Type of application [a]	Number of research reactors involved [b]	Number of Member States hosting such facilities

[7] Based on data from the Agency's Research Reactor Database: http://nucleus.iaea.org/RRDB/.

Teaching/training	163	53
Neutron activation analysis	119	53
Radioisotope production	84	44
Neutron radiography	72	40
Material/fuel irradiation	68	29
Neutron scattering	47	31
Geochronology	25	22
Transmutation (silicon doping)	23	20
Transmutation (gemstones)	19	15
Neutron therapy, mainly R&D	14	12
Other[c]	119	36

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

[b] Out of 239 research reactors considered (226 operational, 13 temporarily shut down, as of 31 December 2018).

[c] Other applications include calibration and testing of instrumentation, shielding experiments, nuclear data measurements, public visits and seminars

123. According to the Agency's Research Reactor Database, 841 research reactors have been built in 67 countries, of which 252 are in operation in 55 countries. The Russian Federation has the largest number of operating research reactors (59), followed by the USA (50), China (17) and Japan (9). Worldwide, 66 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.

124. 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. The Agency encourages research reactor operators to develop or update strategic plans for the use of their facilities. In the past three years, 38 facilities submitted their strategic plans to the Agency for further advice on their sustainable and efficient use.

125. Half the operating research reactors are over 40 years old. Their life cycle can exceed 60 years, but it is of paramount importance that adequate ageing management, refurbishment and modernization programmes be established in time. In view of the general trend of reductions in funding for such facilities and limited succession planning, sound management systems, operation and maintenance and life management programmes will be vital so that they can fulfil their missions cost effectively. With that in mind, Operation and Maintenance Assessment for Research Reactors peer review missions have been undertaken in Bangladesh, the Democratic Republic of the Congo, Portugal and Uzbekistan. Several of the 56 research reactors that are in permanent shutdown status in 22 Member States are expected to start preparing for decommissioning in the near future. In June 2018, the owners of the Halden Boiling Water Reactor in Norway permanently shut down the reactor, which eliminates a major test facility for fuel and material research. In March, Canada's National Research Universal Reactor, a major medical radioisotope producer, was also permanently shut down after 61 years of operation.

126. New research reactors are under construction in Argentina, France, India, the Republic of Korea, the Russian Federation, Saudi Arabia and Ukraine. Several Member States have formal plans to construct new ones, including Belarus, Belgium, Bolivia, the Netherlands, Nigeria, Tajikistan (completion of the Argus-FTI reactor), Thailand, the 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 Agency's first two Integrated Nuclear Infrastructure Review for Research Reactors (INIR-RR) peer review missions, aimed at providing support and guidance to Member States embarking upon a new research reactor project, were conducted in Nigeria and Viet Nam. Zambia hosted an INIR-RR preparatory mission. In September 2018, a pool type 2 MW research reactor, constructed at Trombay north site at Bhabha Atomic Research Centre in India, became operational.

127. 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 2018, the Agency consolidated and expanded its instruments and tools: the Internet Reactor Laboratory, a distance training tool mainly for academic education (broadcasting sessions continued in 2018 for the Africa, Europe, and Latin America and the Caribbean regions); the Research Reactor Regional Schools (RRRSs), for basic training; the Eastern European Research Reactor Initiative (EERRI) for advanced hands-on training, mainly for young professionals; and the IAEA-designated International Centre based on Research Reactor (ICERR) scheme for specific, advanced training for young and senior professionals, currently implemented by six facilities in Belgium, France, Russian Federation and the USA.

128. The French National Institute for Nuclear Science and Technology launched a new multimodal platform, Enhanced Virtual Open Core, to provide education and training on reactor physics and operation.

129. Continued safe, reliable and 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 support models to help Member States select the most feasible option for their scenario.

130. To date, 99 research reactors and four medical isotope production facilities have been converted from use of high enriched uranium (HEU) to LEU or confirmed as being shut down. In November 2018, the miniature neutron source reactor (MNSR) in Nigeria was converted from HEU to LEU fuel, and the irradiated HEU fuel was returned to China in December. The programme for the return of HEU fuel to the USA had so far completed the removal or confirmed disposition of more than 4415 kg of fresh and spent HEU fuel, and the Russian origin return programme had completed the removal of approximately 2280 kg.

131. In January 2018, Curium, a leading nuclear medicine solutions provider, completed the conversion of its target manufacturing to be solely from LEU, leading to approximately 75% of the molybdenum-99 sold in the world today being produced without the use of HEU. Brief outages at some global molybdenum-99 target irradiation facilities and processors in 2018 resulted in some regional supply shortages. Efforts by supply chain management bodies and major international producers, as well as effective mitigation efforts by health practitioners, compensated for some of the production fluctuations. NorthStar Medical Radioisotopes in the USA began producing molybdenum-99 with non-HEU targets in 2018.

132. In October 2018, the Belgian Federal Government decided to make a significant financial contribution (for 2019–2020) for the development of an innovative accelerator-based technology to produce molybdenum-99 without the use of HEU. The Government also decided, in September 2018, to support the development of the Multi-purpose Hybrid Research Reactor for High-tech Applications

(MYRRHA) with a substantial, large scale investment (over the period of 2019–2037). MYRRHA is an accelerator-driven system that will mainly be used to investigate transmutation, develop the next generation of medical radioisotopes and study advanced materials.

C.2.1. New Technologies in Moderators to Produce Cold Neutrons

133. Cold moderators provide neutrons of very low energy by using carefully selected materials at cryogenic temperatures. Such neutrons are particularly favourable for materials science studies. Innovative designs to produce cold neutron beams include the development of pelletized solid moderators, such as the one operating at JINR-Dubna's pulsed IBR-2 research reactor. In solid cold moderators, which are generally made of methane, radiolysis of methane generates hydrogen gas and the resultant swelling may damage the moderator vessel. However, the small pellets in the JINR-Dubna system (Figure C-5) are made of more radiation resistant hydrocarbons and are continuously blown into the moderator vessel, readily removed at the end of their useful life, and therefore reduce the potential for damage. This innovative approach is being applied to both research reactor based and accelerator driven neutron sources. In addition, a number of other important findings on innovative designs, prototyping and real scale testing of such advanced moderators were the outcomes of an Agency coordinated research project completed in 2018.

134. The other main novelty has been the development of liquid cold moderators. This has involved isolating one nuclear 'spin state' in liquid hydrogen with the help of catalysts (i.e. parahydrogen). In such designs, the useful cold neutrons can travel quite long distances without further interaction, enabling construction of low-dimensional cold moderators (fingers, pancakes), around which neutron scattering instruments can be more effectively packed.

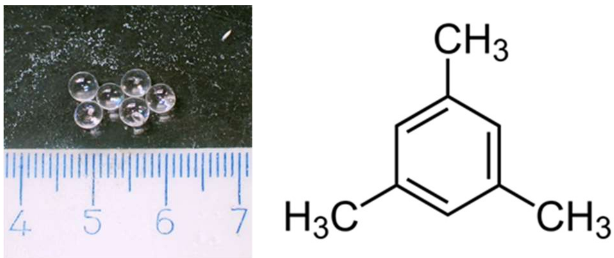

FIG. C-5. Image of pellets made at JINR-Dubna and used to moderate fast neutrons (left), and the schematic representation of their molecular structure. (Courtesy of JINR Dubna.)

D. Radiation Technologies

D.1. Cosmic-Ray Tomography: A Probe from the Stars

135. Muon radiography is an emerging technique and uses naturally occurring background radiation in the form of cosmic ray muons. Terrestrial cosmic ray muons are created when high energy primary cosmic rays interact with the earth's atmosphere producing energetic muons. Their properties are like those of electrons but they have a much larger mass. Cosmic muons are approximately 10 000 times as energetic as a typical X-ray and release energy mainly by ionization. Such muons can penetrate very large structures. They are charged and leave ionization trails as they lose energy as they travel through matter. This allows them to be detected in scintillation and ionization detectors and their tracks to be measured.

136. The main advantage of this technique, based on muon scattering or absorption, is that it is possible to detect density variations of high atomic-number materials in a closed volume (even if embedded) in an intact way without using any radioactive source. Muon radiography requires at least two detector planes that allow definition of the tracks of the detected cosmic muons, and often three or four detector planes are used for better resolution and efficiency. Small objects can be imaged by reconstructing muon trajectories before and after the interaction with the object, while for large targets a 2D image is formed by comparing the flux with a control measurement. Muon radiography results are not necessarily limited to 2D images; the information from several detectors imaging the same volume can be combined to form a 3D image by rotating the target or detectors around it.

137. Various application areas are being targeted world-wide such as measuring the thickness of the magma of a volcano at 1km depth; identifying previously undiscovered cavities of a pyramid in Egypt[8] and underground structures in Naples, Italy[9]. These results suggest muons can be utilized as a new tool for studying civil structures such as buildings, bridges and tunnels. There has been a significant increase in the number of publications on the topic in recent years.

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[8] Morishima, K. et al., Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons, Nature 552, 386-390 (2017).

[9] Saracino, G. et al., Imaging of underground cavities with cosmic-ray muons from observations at Mt. Echia (Naples), Scientific Reports 7:1181 (2017).

D.1.1. Applications

138. The application areas of this imaging technique are still growing and include geoscience, nuclear safety and security, civil engineering and archaeology. In these fields, applications can be found that combine shielding, resolution and time scales for which muon tomography is a suitable imaging method. Figure D-1 visualizes several of the various applications.

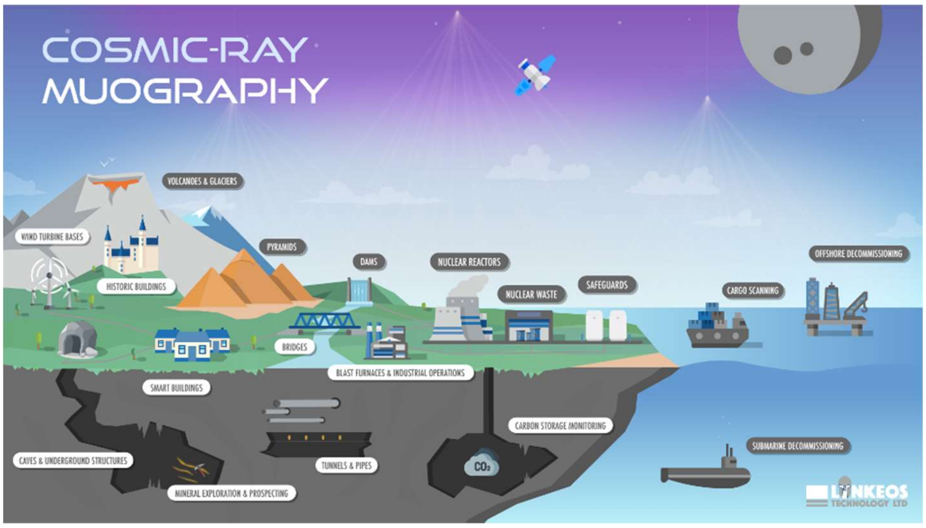

FIG. D-1. Schematic infographic illustrating the various applications of muon tomography (Source: Lynkeos Technology Ltd., UK)

139. The most typical application in geoscience is the imaging of the inside of volcanoes. This method has been used by volcanologists in France, Italy and Japan, for example.[10, 11, 12] Using this technique, it is possible to predict volcano eruptions and thus prepare in advance and minimize the effects of natural disasters. Figure D-2 shows the first high-definition muographic image of the Sakurajima volcano, Japan.

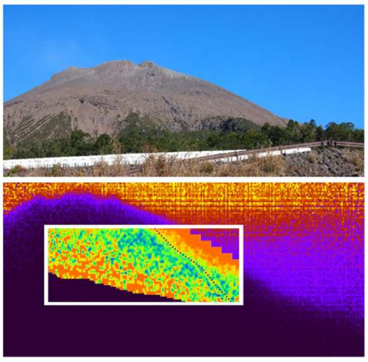

FIG. D-2. Successful imaging of an erupting volcano. The lower inset image shows the interior of the volcano with 10 m × 10 m resolution (Photo: Oláh et al.[9], University of Tokyo, Japan)

140. The development of muon tomography systems for industrial applications is currently a challenge for the scientific community. Industrial equipment like blast furnaces and rotating furnaces can suffer

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[10] D'Alessandro, R., Volcanoes in Italy and the role of muon radiography, Phil. Trans. R. Soc.,. Volume 377, Issue 2137, Jan. 2019.

[11] Oláh, L., Investigation of the limits of high-definition muography for observation of Mt. Sakurajima, Phil. Trans. R. Soc., Volume 377, Issue 2137, Jan. 2019.

[12] Oláh, L., Tanaka, H. K. M., Ohminato, T., and Varga, D., High-definition and low-noise muography of the Sakurajima volcano with gaseous tracking detectors, Scientific Reports 8 3207 (2018) 1-13.

inner wear that cannot be measured easily with currently available techniques. These kinds of facilities are large enough for both transmission and scattering imaging and both can be used to quantify wear. Therefore, muon tomography can help in the diagnosis process, making the productive processes of the companies more efficient in terms of energy saving and economic costs. Further civil engineering applications include the monitoring of historical buildings, large structures like bridges and wind turbines and potentially also structures on oil rigs. After the recent bridge disaster in Genoa, Italy, civil engineering applications may now see a faster development.

141. Nuclear safety and security offer other important applications for muon radiography. The very fact that radioactive material and waste is stored in shielded containers that are designed to contain the radiation also means that similar radiation cannot be used to image their contents. The ability of muon radiography to distinguish between nuclear fuel and other metals is crucial for applications in nuclear security, in particular for cargo screening for national security,[13] but also for applications related to safeguards, e.g. the monitoring of dry storage casks and the characterization of legacy radioactive waste with complex geometries.[14, 15]

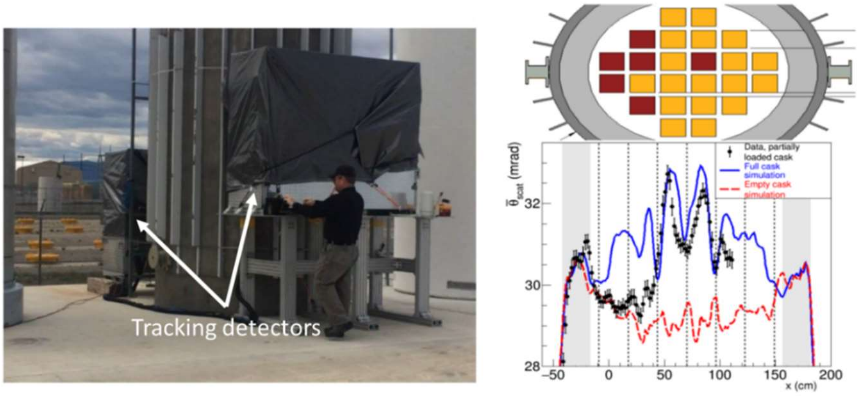

FIG. D-3. Photograph of muon trackers placed on two sides of a partially loaded MC-1 storage cask (left). A schematic showing the location of missing (red) and loaded (yellow) fuel bundles (top right). Experimental signal (black) compared to Monte Carlo expectations of a fully loaded (blue) and empty (red) cask (bottom right). (Photo: Christopher Morris, Los Alamos National Laboratory, USA).

142. The search for special nuclear materials inside cargo containers was perhaps one of the first potential applications of muon tomography. The imaging of the contents of nuclear waste containers and quality assurance for nuclear waste treatment processes are further key applications in the field of nuclear safety.[16] A demonstrator system has recently been deployed at the Sellafield site in the UK. Finally, nuclear reactors themselves can also be imaged with cosmic muons. In Japan, a team of researchers has worked to image the corium in the Fukushima Daichi reactors, supported by simulations that indicate that this should be possible.[17]

143. It is expected that muon radiography will become a technology that finds its place between other imaging technologies, especially with its particular advantages: no radiation dose beyond natural

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[13] Durham, J. M., et al., Verification of Spent Nuclear Fuel in Sealed Dry Storage Casks via Measurements of Cosmic-Ray Muon Scattering, Phys. Rev. Applied 9 044013 (2018).

[14] Morris, C. L., et al., Application of muon tomography to fuel cask monitoring, Phil. Trans. R. Soc., Volume 377, Issue 2137, Jan. 2019.

[15] Yang, G., et al., Novel muon imaging techniques, Phil. Trans. R. Soc., Volume 377, Issue 2137, Jan. 2019.

[16] Mahon, D., et al., First-of-a-Kind Muography for Nuclear Waste Characterisation, Phil. Trans. R. Soc., Volume 377, Issue 2137, Jan. 2019.

[17] Miyadera, H., et al., Imaging Fukushima Daiichi reactors with muons, AIP Advances 3 052133 (2013).

background; its ability to penetrate thick objects; and its ability to measure both density and atomic number. The main disadvantage of the technique is the long time exposures needed for many applications.

E. Human Health

E.1. Calibration Services for Modern X-ray Mammography

E.1.1. Background

144. Mammography is a breast imaging technique that uses low-dose X-rays to screen for and diagnose breast cancer. It is used in population-based screening programmes to detect breast cancer in its early stages, thereby exposing large numbers of women to radiation during the process. It is important that the radiation dose used for the examination should be measured accurately so that the risk and the benefit can be optimized. The World Health Organization has identified quality assurance (QA) as a key criterion for successful implementation of mammography imaging. Through QA, both the radiation dose and quality (radiation spectra) of the mammography system can be modified to achieve a better image quality, while keeping the radiation dose as low as possible.

145. Accurate dosimetry has an important role in this optimization process. Dosimetry equipment used for these measurements needs to be calibrated in a recognized calibration laboratory. The calibration must be traceable to the International System of Units so that the doses measured in different institutions are all traceable to a unique international standard, and thus easily comparable. This is normally the responsibility of a secondary standards dosimetry laboratory (SSDL), which provides traceable calibrations for hospitals.

E.1.2. Radiation Qualities

146. Conventionally X-ray tubes with a molybdenum anode and molybdenum filtration were used for film-screen mammography. This radiation quality has been used as a standard for clinical dosimetry and calibrations. Modern mammography units employ a wider range of radiation qualities, achieved through different anode/filter combinations and tube voltage selections. Digital mammography systems often use tungsten anode-based X-ray tubes. Clinically this enables higher image quality at a lower patient dose.

147. Radiation qualities used in SSDLs are standardized and currently based on molybdenum anode/filter combinations. The challenge is to fully cover the clinically-used range of radiation qualities so that accurate measurements can be achieved in all clinical situations. Molybdenum anode X-ray tubes are needed only for mammography calibrations whereas a tungsten anode is typically used for another type of X-ray diagnostic radiology imaging and related calibrations. This can present an economic strain for SSDLs that need to acquire a molybdenum anode X-ray system just for mammography calibrations.

E.1.3. Dosimeters

148. Traditionally ionization chambers have been used for medical dosimetry. The response of ionization chambers is not normally strongly dependent on the energy of the incident beam. They can therefore be used in measurements over a wide range of different radiation beam qualities (energies). The half-value layer (HVL) is used as a surrogate for specifying the radiation beam quality. The calibration coefficients of ionization chambers can therefore be provided for some radiation qualities,

and coefficients for other energies can be derived by interpolation between different HVL values. In this way, accurate dosimetry can be performed for the complete range of different mammography radiation qualities that are available in hospitals.

149. Recently, the clinical use of semiconductor-based dosimeters is increasing and gradually replacing ionization chambers because these more compact dosimeters are easy to handle and can also be used to measure several other quantities (e.g. HVL, tube voltage) with only one exposure. However, the inherent energy dependence of their response is more pronounced compared to ionization chambers. Therefore, multiple internal compensation methods based on the radiation quality are developed by the manufacturers to compensate for this effect. However, many users do not fully understand how these corrections are made. This sets additional challenges for the dosimetry and calibration of dosimeters used in mammography.

E.1.4. Calibrations

150. Dosimetry equipment should be calibrated regularly in SSDLs. In a calibration procedure, the response of a dosimeter is compared to the national traceable reference standards and a calibration coefficient for the dosimeter is determined. Typically, SSDLs cannot provide calibrations for the large number of possible beam qualities that are used clinically.

151. For the calibration of ionization chambers, the variation of radiation quality is not an issue, due to the negligible energy dependence of their response. However, this is not the case with semiconductor dosimeters which have a more pronounced energy dependence.

E.1.5. Further Developments

152. The Agency's Dosimetry Laboratory (DOL) provides the IAEA/WHO SSDL network members with access to the entire range of radiation qualities that may be requested for mammography dosimetry. Several dosimeter types have been calibrated at the DOL. Based on the results (Figure E-1) conducted in the DOL, some new semiconductor-based dosimeters were found to compensate for the changes (correct the displayed value) in radiation qualities very well. This means that they could be used for measurements in the large range of clinically-used radiation qualities.

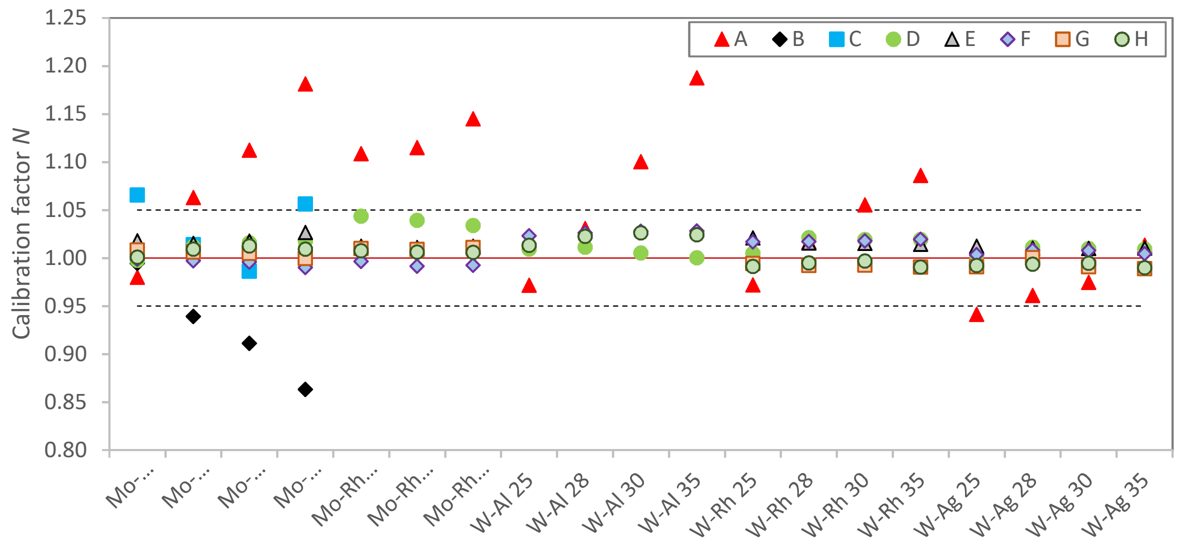

FIG. E-1. Calibration factor N (mGy/mGy) measured at the Agency's Dosimetry Laboratory for eight semiconductor based dosimeters (A–H) as a function of radiation quality.

153. However, SSDLs in Member States do not necessarily have all these radiation qualities available for the calibration of dosimeters used in mammography. Therefore, manufacturers of semiconductors are encouraged to develop a standardized method, which could be used for the calibration of their dosimeters in standardized conditions.

154. The use of molybdenum anode/filter machines to produce a standard set of radiation qualities for the calibration of dosimeters used in mammography does not represent the current clinical trend. Therefore, new standard radiation qualities using a tungsten anode should be developed. The semiconductor-based dosimeters should include a calibration mode in which these standard radiation qualities could be used in a way that the performance of the dosimeter in all clinical radiation qualities could be verified and confirmed. This will avoid mistakes in dosimetry and contribute to quality diagnostic or screening of breast cancer worldwide.

E.2. Radio-guided Surgery in Gynaecological Cancers

E.2.1. Background

155. Cancer is among the leading causes of mortality worldwide. In vulvar, endometrial and cervical malignancies, the use of radio-guided surgery is associated with decreased short-term and long-term morbidity when compared with complete lymph node dissection.

156. The sentinel lymph node (SLN) is the first regional lymph node that directly drains the lymph from the primary tumour. Thus, SLNs are considered the first nodes to receive the seeding of lymph-borne metastatic cells. SLN mapping and biopsy has become a routine technique in cancer surgery (breast and melanoma), contributing to minimizing the surgical procedure.

157. SLN detection provides prognostic information on nodal status and can help avoid morbidity from overtreatment. Furthermore, as there are no imaging modalities able to detect microscopic metastases, SLN biopsy is considered the only reliable method for screening lymph nodes and identifying micro-metastatic disease in regional lymph nodes.

E.2.2. Cervical Cancer

158. Cervical cancer is the third most frequent gynaecological cancer in developed countries but the most frequent in developing countries and the primary cause of death in women of child-bearing age. Generally, it spreads locally to adjacent pelvic organs, but can also spread to locoregional lymph nodes and, in some rare cases, lungs, liver, bones or brain haematogenous metastases have been seen. The usefulness of SLN detection in cervical cancer has been studied in a large series of 507 women and in reviews that comprised 831 patients. A detection rate of 93.5% and 96%, a high negative predictive value (94% and 97%) and a false negative rate of 8% were found using the combined technique. A significant result is the higher detection rate and negative predictive value in tumours of less than 2 cm (94% vs 84% and 99% vs 89%).

E.2.3. Endometrial Cancer

159. Endometrial cancer is the most common malignancy of the female genital tract in developed countries. Pelvic or paraaortic node involvement denotes a worse prognosis, with a five-year survival rate of between 44% and 52%. In high-risk endometrioid cancer (G3, >50% myometrial involvement) or in patients with a high-risk tumour histology (clear cell, papillary serous, carcinosarcoma) the standard of care is a surgical staging, including pelvic and paraaortic lymphadenectomy. But in low risk endometrial cancer the incidence of nodal invasion is very low and there is still no clear consensus for management. In some patients a histological low grade is modified and increased after pathological

examination of the whole tumour sample. In these cases, a prior surgical staging would have been of benefit.

160. The diagnosis of nodal invasion can modify management and the introduction of adjuvant therapy. In addition, it is important to emphasize the fact that the majority of endometrial cancer patients are of high surgical risk due to obesity and associated co-morbidities. In this setting, the SLN concept may significantly decrease postoperative morbidity if systematic lymphadenectomy could be avoided even in patients with high risk tumours. The use of SLN detection can provide not only a surgical staging without increasing the number of complications that can result from a complete lymphadenectomy, but also increase the sensitivity of the staging, performing immunochemistry on selected lymph nodes. Although several studies of SLN detection in endometrial cancer have been carried out, there is still not enough scientific evidence for validation at this point.

E.2.4. Ovarian Cancer

161. The incidence of positive lymph nodes in early stage ovarian cancer is low, ranging from 5.1% to 15%. Pelvic and paraaortic lymphadenectomy involves increasing surgical time and possible morbidity. However, SLN detection in ovarian cancer should be considered.

E.2.5. Future Trends

162. The most relevant advancement in gynaecological cancer is the introduction of intra-operative instruments such as the portable gamma-camera. This device provides an intraoperative image to locate SLNs before resection. Once removed, an additional image of the surgical field can confirm successful resection by an absence of activity. The procedure takes between 5 minutes (in vulvar and cervical cancer) and 15 minutes (in endometrial cancer), which is a relatively short period in a complete surgery procedure.

163. The hypermetabolic behaviour of gynaecological cancer makes diagnosis and positron emission tomography (PET)-guided localization of recurrent masses feasible. Recurrent disease, easily diagnosed by PET/computed tomography, can present as a massive spread along the abdominal cavity, which must be treated with chemotherapy; or as a small isolated tumoral focus. In these particular cases, the use of a hand-held intraoperative PET probe can guide surgery, identify the tumoral mass and differentiate it from normal or scar tissue. PET-guided surgery is especially useful in the detection of non-palpable lesions, or lesions covered by fibrotic tissue. The main technical difficulty is the high physiological uptake in surrounding tissue: liver, spleen, kidneys, bladder, etc. This high activity, together with the low spatial resolution of some devices, makes it unsuitable as a guide for margin resection. One of the benefits of this kind of surgery is the decrease in surgical morbidity, due to the direct lesion localization with the probe and a reduction in the incision size. Before surgery a PET image is recommended, to localize the tumoral foci and to plan resection.

164. Despite the potential benefits of this procedure, PET-guided surgery is still not widely used. The main problems are: a) non-specific localization, because the probe can detect either tumoral and inflammatory tissue; b) technical difficulties, as described above, due to the high activity in the abdominal cavity (a minimum ratio of 1.5:1 is recommended) and because the size of the probes does not allow for the use of laparoscopic surgery; c) radiation of the staff, although some studies define an annual maximum of 260 hours for this type of surgery; and d) financial reasons.

165. Recently, a new tracer has been tested in gynaecological malignancies, especially in cervical cancer; the new equipment employed to visualize this agent consists of a multispectral fluorescence camera that provides an intra-operative visualization of the tracer. A fluorescent tracer (indocyanine green) is injected at the beginning of surgery and visualized during the pelvic surgical examination.

F. Food and Agriculture

F.1. New Developments Pointing to a Paradigm Shift for Food and Phytosanitary Irradiation

166. Irradiating food 'in-house' as part of a normal food business operation has long been a dream. Currently food irradiation is often outsourced to large separate facilities operated by specialist contractors, but the development of new irradiators, dosimetry systems and applications are paving the way for a new approach. Technology is shrinking the size of electron beam and X-ray generators and recent developments in machine-source irradiation indicate that irradiation units may be more easily installed on food-packing lines or as part of a food manufacturing facility.

167. Irradiation involves processing food by passing it through a beam of ionizing radiation. The beam can pass through packaging and through food, just as an X-ray can pass through a person's body, but unlike medical X-rays, the purpose is to deposit energy to bring about some change without increasing temperature significantly. Solid, pre-packaged and even frozen food can be treated in this way with minimal negative changes to the food, while the packaging protects the food after treatment. But it is a costly process that takes time so producers would not needlessly irradiate food. It is used only when it brings about some beneficial change to either improve or maintain a high-quality product. Examples include: using irradiation to ensure food is free of food poisoning bacteria; to reduce the number of spoilage organisms and therefore keep food fresher for longer; to prevent sprouting without using chemicals (e.g. in ginger, yams, garlic, onions and potatoes); or as a phytosanitary treatment to prevent the spread of invasive organisms (flies, insects, weevils and mites, and potentially slugs, snails and even unwanted seeds). The latter purpose is especially important for consignments of fresh fruits and vegetables in which pests may hitch-hike and, through international trade, establish themselves in new locations where they may damage local environments and agriculture. As the use of fumigation chemicals is increasingly restricted due to health and/or environmental concerns, irradiation use leaves no harmful chemical residues and has minimal negative effects on food quality.

168. Powerful sources of ionizing radiation are required, which need to be managed correctly. Most food is irradiated using gamma rays from cobalt-60. The cobalt-60 gamma rays are emitted at energies of 1.17 and 1.33 MeV with zero mass, so they can penetrate through large volumes of bulky products (pallets loaded with sacks of spices can be irradiated in one go, for example). The radiation source diminishes at a rate of about one per cent per month (the half-life of cobalt-60 is about five years) and so the exposure time needs to be increased slightly each month to deliver the same amount of energy (radiation dose). With time, source replenishment is needed.

169. Some food is irradiated using electron beam (EB) radiation. The EB may have energies up to 10 MeV; each electron in the beam has an overall negative electrical charge and a small but appreciable mass. Although this means that EBs can be turned on when needed and directed and focused using magnetic fields, it also means that they readily interact and collide with atoms in food, rapidly transferring energy at a high rate over a relatively short distance: EBs do not penetrate very deeply and they are suitable for irradiating food packs of several centimetres or so in depth.

170. Considerably fewer foods are treated by X-ray irradiation, during which a metal target is bombarded with an EB to convert the kinetic energy of the electrons into X-rays, generally with energies up to 5 MeV, but in some countries up to 7.5 MeV. The X-rays are as penetrating as gamma rays because they have zero mass, so X-rays too are useful for irradiating large pallets of bulky foods in one go. However, a lot of energy is wasted as heat when the EB is converted in the metal target with only a few per cent resulting in X-rays.

171. Both EBs and X-rays are produced using machines, and different beam characteristics and energies can be established by changing machine parameters or by design. In contrast to cobalt-60, these sources can be switched off when not needed. Also, history shows that machines are very amenable to technological innovations.

172. With either radionuclide or machine source irradiation, the current business model usually involves an irradiation facility being a stand-alone service provider that contracts its irradiation services to others. Commercial irradiation facilities are often located on major trade routes or transport hubs, such as freight terminals that serve ports and airports. The facility itself is essentially a large warehouse with an irradiator at its centre. Food enters the irradiation chamber from the non-irradiated sector (goods received area) of the warehouse, it has a timed exposure to the radiation beam and therefore a specific minimum radiation dose, and exits the chamber into the irradiated sector (goods for dispatch area) of the warehouse. It is held here until it can be certified as having received the correct radiation treatment by checking the recorded exposure time and the confirmatory readout of dosimeters that accompanied it through the process. Once certified as correctly irradiated, the food is shipped to wherever the owner specifies.

173. This established way of doing things is likely to continue, but new technology is enabling irradiation units to become miniaturized and although these miniaturized units currently offer low energy beam sources, they are being used in industry to sterilize packaging material, medical equipment and biological samples in factories, as part of the normal manufacturing process. Over time small EB and X-ray generators may become more powerful and so more useful for food irradiation. Such developments point to a future where food could be irradiated on packing lines, during manufacture or when freshly harvested at the farm. Now is the time to lay solid technical foundations to support EB and X-ray irradiation for this paradigm shift to eventually offer new business opportunities in food and phytosanitary irradiation. The Agency, in collaboration with the Food and Agriculture Organization of the United Nations, is aiming to accelerate research and development to facilitate practical EB and X-ray techniques to unlock their future potential for new and improved food irradiation treatments.

174. Current research activities in the USA include the construction of a portable low energy (160 keV) cabinet X-ray irradiator[18] to generate ionizing radiation to treat fruit in boxes for insect disinfestation as a quarantine treatment. Research in the Republic of Korea is evaluating the effects of low-energy X-rays on the microbiological, physicochemical, and organoleptic characteristics (colour, taste, smell and texture) of foods. The concept is for small X-ray cabinets to be used in hospitals to ensure food safety for at risk patients (e.g. the immuno-compromised). Collaborative work between researchers in Japan and Poland is leading to a new approach for the irradiation of food and agricultural products that is related to the limited penetration of electrons with energy below 300 keV. This is a new application for the elimination of bacteria, moulds and yeasts from the surface of food products. Treatment was compared to conventional (10 MeV) EB irradiation of black pepper corns, white pepper corns and whole allspice. The surface treatment was as effective as conventional irradiation at reducing and eliminating microbes.[19]

175. Tools to assist machine source irradiation facilities are also being developed. In China, a proof of concept has been developed for an X-ray device to scan boxed products prior to radiation processing to determine if the food package is within specification for correct EB irradiation.[20] A similar concept is

[18]Follett, P., Kirk, R., A portable cabinet X-ray machine to control insects in exported fruit https://www.cherrygrowers.org.au/assets/PASE_Portable_X-ray_Machine.pdf

[19] Gryczka, U., Migdał, W., Bułka, S., The effectiveness of the microbiological radiation decontamination process of agricultural products with the use of low energy electron beam, Radiation Physics and Chemistry 143 (2018) 59-62.

[20] Qin, H., et al., Concept development of X-ray mass thickness detection for irradiated items upon electron beam irradiation processing, Radiation Physics and Chemistry 143 (2018), 8-13.

being developed in Viet Nam but here gamma rays from small collimated cobalt-60 sources are used to scan the boxed products for testing prior to EB irradiation. Both devices have been piloted in commercial EB facilities — they give a rapid measurement of mass thickness (a key parameter in EB) and use different algorithms to accurately predict dose distribution from EB irradiation. The effectiveness of EB irradiation can be assessed rapidly and the optimized product configuration can be derived by simulation prior to actual treatment. In latest research in China, a system is being tested that will simulate dose distribution in three dimensions, which could revolutionize dosimetry in radiation processing.

176. In 2015, the food-engineering group Bühler forged a strategic partnership with COMET, a producer of small EB lamps. Together they have produced a machine for microbial decontamination of dried food using low-energy EBs[21]. Several of these new devices are being evaluated at different spice processors. Mevex, an EB and X-ray facility provider, has developed "The Mevex X-ray Box", a compact self-shielded X-ray system for research or for small scale commercial processing of high value commodities including food and agricultural products. The irradiator plus shielding has a footprint of about two square metres and is available with energies up to 2 MeV. It is designed to deliver high dose rates in products up to 40 cm high, on a 40 cm diameter turning table. NucTech, a provider of large EB and X-ray facilities based in China, is working to further develop a novel mass thickness detection tool that can be made available commercially for use in EB facilities to examine, validate and possibly dose map products prior to irradiation, saving time and money and improving productivity.

F.2. Nuclear Technologies for Rapid Climate Change Adaptation of Crops and Cropping Systems

177. Drought, extreme temperatures, flooding and soil nutrient deficiencies or mineral toxicities impact crop yields directly through their effects on plant establishment and growth, and indirectly through their influence on the nature and intensity of biotic stresses such as diseases, insects and weeds. Without proper adaptation measures for crop production, climate change will reduce crop yields leading to food insecurity and the breakdown of food systems, especially in developing nations. It can also result in changes in the geographical distribution of crop species.

178. Catastrophic crop losses resulting from climate change call for innovative breeding pipelines to ensure global food security. In the post-genomic era, the combination of plant mutation breeding, marker-assisted selection and high-throughput phenotyping constitutes a powerful recipe for rapid plant adaptation to climate change. Plant breeding routinely strives to improve crop performance in the face of the abiotic and biotic stresses that crop production faces during each growing season.

F.2.1. Marker-Assisted Mutation Breeding for Faster Development of Climate-Smart Varieties

179. Plant mutation breeding remains the fastest approach to creating new genetic variation for rapid adaptation to climate change. Combining mutation breeding with cost-efficient, high-throughput next-generation genotyping and with precision high-throughput phenotyping is key to accelerating such adaptation. This process helps scientists to understand the molecular bases of the genetic variations created by mutation breeding, leading to the development and use of molecular markers that speed up selection and variety development. Thus, molecular marker technologies based on genome-wide association studies, as well as the more focused identification, validation and use of genetic associations of a specific allele/gene family/gene pathway with phenotypic performance, facilitate faster breeding.

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[21] Hertwig, C., Meneses, N., Mathys, A., Cold atmospheric pressure plasma and low energy electron beam as alternative nonthermal decontamination technologies for dry food surfaces: A review, Trends in Food Science & Technology 77 (2018) 131-142.

180. The Agency, in collaboration with FAO, has now established a workflow for the cost-effective identification of induced mutations causing specific phenotypes, and has started to transfer this workflow to Member States through fellowship training. Molecular biology protocols have been developed and the computational resources required for data analysis are currently being put in place. The workflow facilitates genetic mapping approaches supported by next generation sequencing. A major achievement in 2018 was the application of a molecular marker assay for the first time in the Agency's laboratories, specifically on a feed quality trait in barley (orange lemma). Causative mutations for this trait have been identified and a marker assay developed. The genotyping assay is now being tested in a barley breeding programme aimed at introgressing the orange lemma trait into a hooded winter forage barley. The assay correctly predicts the phenotype and thus is useful for marker-assisted selection. In addition, a pilot study is underway on early-maturing, short-statured sorghum, which is attempting to map the traits by whole-genome sequencing of several hundred individuals of segregating populations of sorghum, followed by the analysis of contrasting genotypes to identify the causative genetic loci (Figures F-1, F-2).

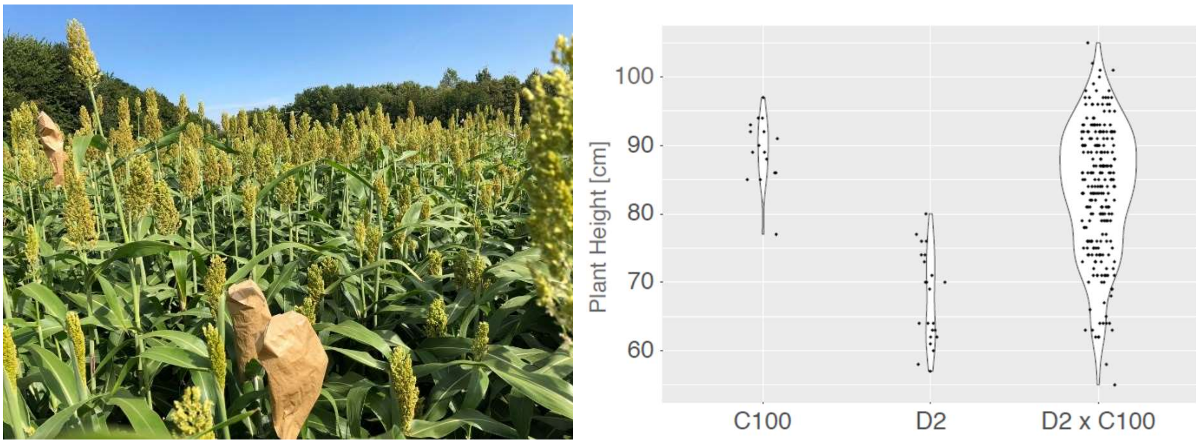

FIG. F-1. Plants growing in a field in Seibersdorf, Austria (summer 2018); mutant dwarfism segregates in Mendelian fashion. Image at right shows plant height distributions of wildtype, mutant, and F2 progeny.

181. While mutation breeding coupled with molecular marker technology is the eventual goal for speeding crop adaptation to climate change, stand-alone mutation breeding continues to be used to develop varieties adapted to adverse climatic conditions. Through the transfer of mutation breeding technology, Pakistan recently released three cotton mutant varieties adapted to high-temperature stress, and with sustained fibre yield and quality. Approximately 20% of the cotton area in Pakistan is now covered by these mutant varieties, and this proportion is expected to increase to 30–40% in the next 2-3 years. Similarly, farmers in Zambia and Zimbabwe have recently seen a 10–20% increase in cowpea yields from varieties developed through mutation breeding that show increased drought tolerance and insect resistance.

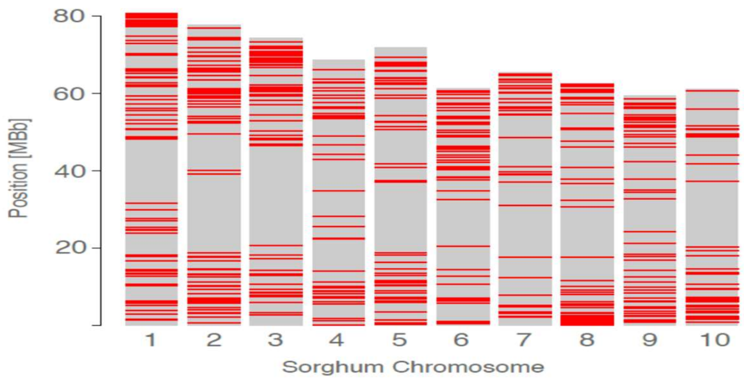

FIG. F-2. Distribution of single nucleotide polymorphisms and small indels across the sorghum chromosomes as identified by whole-genome sequencing of six mutant lines.

F.2.2. X-Ray Computed Tomography for High-Throughput Non-Invasive Plant Phenotyping

182. The lack of facilities to perform non-invasive screening of whole plants or plant tissues at high throughput is recognized as an important bottleneck in crop improvement today, specifically at the stage of selection of better performers. Nuclear magnetic resonance imaging has become increasingly popular in understanding plant vascular function, i.e. that of the xylem and phloem, and the related hydrodynamics. A related nuclear technology, X-ray computed tomography (CT), is also now routinely being used for non-medical applications including plant sciences, and X-ray CT estimates predictive of plant morphological and anatomical traits are increasingly being used in plant phenotyping. Examples of X-ray CT analysis in plant sciences include the screening of plant survival under water stress; evaluation of plant shade tolerance and leaf light interception; analysis of root diseases; and root system development and root–root interactions. The advantage of these technologies comes primarily from their non-invasive nature and the ability to quantify physiological processes in real time. Improvements in instrumentation continue to be made for image capture at both the macroscopic and microscopic scale, while high-throughput use of the X-ray CT is gradually increasing. Complementing established genomics and molecular workflow in plant mutation breeding, and existing phenotyping protocols, with non-invasive nuclear imaging techniques in high throughput will enable an accelerated plant mutation breeding pipeline.

F.3. Innovative Application of Isotopic and Nuclear Technologies in Animal Nutrition

183. By 2050, the global demand for animal-origin food is projected to increase by 60–70%.[22] To achieve the huge task of increasing supplies of milk, meat, eggs and other edible animal products in a sustainable fashion, within the given timescale, the livestock industry will require technology-based intensification of its production systems. The feed and forage supplies and access to good pasture, grasslands and rangelands will need to be doubled to meet the projected demand in animal nutrition. The situation is further compounded by increasing feed–food competition between animals and humans and the impact of animal production on the environment.

184. Currently, nearly 800 million tonnes of cereals (one-third of total cereal production) are used in

[22] FAO, The future of food and agriculture: Trends and challenges (2017) FAO, Rome http://www.fao.org/3/a-i6583e.pdf

livestock feeds and by 2050 it is projected to be over 1.1 billion tonnes[23]. In 2006, global greenhouse gas (GHG) emissions from livestock operations were estimated to be 7.1 gigatonnes of CO_2-eq per year, representing 14.5% of all anthropogenic GHG emissions[24]. Innovative research and development, integrating nuclear techniques with conventional technologies, is needed not only to improve the current stall-feeding and grazing systems but also to expand the horizon of feed and forage sources to embrace unutilized grassland and rangelands, industry by-products, food waste, mass production of unicellular algae and aquaponic forage production, and to explore other lesser known and unconventional animal feeds. This will help build a quality dataset and provide the information needed to inform political decisions and potential investors.

185. More than 40% of earth's terrestrial areas, excluding Greenland and Antarctica, are covered by grasslands, which, if optimized for utilization as a feed source for livestock, would benefit many millions of farmers worldwide.[25] In the tropics, ruminants are the major livestock species and their production is heavily based on grazing on natural pastures (Figure F-3). Nuclear and isotopic techniques can be used to build a dataset on feed intake, diet selection and nutrient contents of grasses and browse species that constitute animal diets. This is required for various management decisions such as optimization of forage allocation to different types of animals, selection of appropriate plant species for reseeding degraded pastures and rangelands, and designing appropriate supplementation strategies. Efficient use of grasslands also offers possibilities for increasing carbon sequestration, land reclamation and livestock productivity.

FIG. F-3. Co-rearing of grazing and browsing species is a common practice in Zimbabwean communal grasslands.

F.3.1. Nuclear Techniques to Investigate and Improve Grazing Animals' Nutrition

186. Conventional technologies involving in-vivo feeding trials, in-vitro analysis of digestibility and bromatological analysis of feeds and fodders used in stall-feeding system were found to be not effective for the estimation of voluntary feed intake and diet selection in grazing animals. Recent advances in the development of tools and protocols for the application of a combination of innovative nuclear and conventional technologies bring solutions to the challenges where feed intake, diet selection and digestibility can be analysed and estimated in animals grazing heterogeneous pastures.

187. The Agency has been working with Member States to develop animal nutritional tools to provide an integrated application of compound specific stable carbon-13 isotopes of long chain n-alkanes and near-infrared spectroscopy (NIRS) for the estimation of ruminant livestock feed intake, diet selection, diet composition and digestibility. This helps to optimize livestock nutrient intake by feed supplementation whilst grazing, preventing overgrazing of pastures and grasslands.

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[23] Makkar, H. P. S., Review: Feed demand landscape and implications of food-not feed strategy for food security and climate change, Animal 12 (2018) 1744-1754.

[24] FAO, Key facts and findings, http://www.fao.org/news/story/en/item/197623/icode

[25] Suttie, J. M., Reynolds, S. G., Batello, C., Grasslands of the World (2005) Rome, FAO http://www.fao.org/docrep/008/y8344e/y8344e05.htm

F.3.2. N-alkanes Help Estimate Feed Intake, Digestibility and Diet Selection

188. All higher plants that constitute animal diets have a layer of wax on their outer surfaces (n-alkanes) which differ significantly in different species and their quantitative data can be analysed to differentiate the plant species that constitute diets of an animal. Thus, n-alkanes have been used as faecal markers to estimate plant digestibility, and a combination of these data with faecal output has been used to calculate animals' feed intake. N-alkanes as faecal markers can originate from the diet (internal markers) or be administered orally (external markers). Although n-alkane as a faecal marker can differentiate many plants in ruminant diets, it cannot discriminate between all plants, especially not between dozens of plants in heterogeneous pastures. Carbon isotope enrichment of n-alkanes, however, can accurately discriminate plant species in heterogeneous pasture. A combined application of n-alkane and carbon-13 technology has proved highly effective for the estimation of feed intake, diet composition and digestibility. Compound specific carbon isotopes (carbon-13/carbon-12) are analysed by using gas chromatography/combustion isotope ratio mass spectroscopy following saponification, extraction and purification. Furthermore, a promising innovative laser-based technology, cavity ring down spectroscopy, has been successfully used for the determination of carbon-13 content, providing measurements in a shorter time and with a simpler pre-treatment of samples.

F.3.3. NIRS Analysis of Residual Nutrients in Faeces Helps Estimate Nutrient Contents, Voluntary Feed Intake and Diet Selection

189. NIRS analysis involves illumination of feed or faeces samples with a broad-spectrum (many wavelengths or frequencies) of near infrared light, which can be absorbed, transmitted, reflected or scattered by the sample of interest. The illumination is typically in the wavelength range of 800-2500 nm. The light intensity as a function of wavelength is measured before and after interacting with the sample, and the diffusion reflectance, a combination of absorbance and scattering, caused by the sample is calculated. NIRS provides qualitative data on crude protein, fibre contents, proportion of plant species and morphological components, voluntary feed intake and diet digestibility. NIRS analysis provided 60–85% smaller standard deviations when split samples were analysed by both wet chemistry and NIRS using double blind techniques. This indicates that there are fewer human errors with NIRS and data are more consistent than those derived from the conventional wet chemistry analysis.[26]

190. NIRS has become a versatile technique with no sample preparation, decreased costs and analysis time, and the ability to scan samples through glass and packaging materials.

F.3.4. Energy Dispersive X-ray Fluorescence Accurately Determines Mineral Content in Forages

191. Forages constitute the bulk of ruminants' diets; however, their mineral concentration vary greatly, which affects the performance and health of animals. Energy dispersive X-ray fluorescence (EDXRF) is a non-destructive multi-mineral spectroscopy technique that makes mineral analysis and estimation simple, direct and consistent. The technique involves scanning dried and ground forage samples from a wide range of fresh plants, hays or silages at 20–40 keV associated with an aluminium filter and calibration using appropriate software, for example Bruker SpectraEDX (Bruker, Hamburg, Germany).[27] When determining the concentration of common minerals in ruminant rations (sodium, magnesium, phosphorus, sulphur, chlorine, calcium, potassium, manganese, iron, copper and

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[26] De Ondarza, M. B., Ward, R., Accurate analysis: NIRS versus wet chemistry, Hoards Dairyman (February 2013) 129, http://www.foragelab.com/Media/Accurate%20analysis%20NIRS%20versus%20wet%20chemistry.pdf

[27] Berzaghi, P., Lotto, A., Mancinelli, M., Benozzo, F., Technical note: Rapid mineral determination in forages by X-ray fluorescence, Journal of Dairy Science 101 (2018) 9967-9970.

zinc), the coefficient of determination ranged between 0.93 and 0.99 while the coefficient of variation was within an acceptable range (5–14%). EDXRF can be applied in the field in diverse animal production systems to determine mineral concentration. The data gleaned will provide the base for mineral supplementation to enhance the health and productivity of animals.

192. Feeding is key to profitable and sustainable animal production. It influences the animal's growth, health, welfare, productivity and product quality. It accounts for more than 70% of the cost of any livestock operation. Feeding is not only affected by resource availability but also has a direct impact on the resource base (pasture, grassland and environment). Meeting the ever-increasing demand for food of animal origin requires improving livestock productivity and limiting its impacts on the environment. To achieve this, all three technologies described above, when validated and applied together, can provide a complete answer on the nutrients available in the feeds and forages, their accessibility and palatability for animals and their digestibility to support nutrient and energy conversion towards growth, health and performance. The carbon-13 and n-alkane techniques determine which plants were consumed and in which quantities, the EDXRF technique determines the mineral composition of the diet, and NIRS estimates residual nutrient compositions in livestock faeces. NIRS technology is currently used in stall-fed animals to estimate the feed intake, diet composition and nutrient contents. For grazing animals, the carbon-13 and EDXRF technologies can be used in combination with NIRS, and all three together could give an overall estimate of nutrients in feeds, feed intake and diet composition (Figure F-4). Further, both NIRS and EDXRF technologies are mobile, require minimum maintenance, have lower human error rates than wet chemistry and do not require any sample preparation. Future advances will include an integrated approach between these three technologies to determine the quality and quantity consumed.

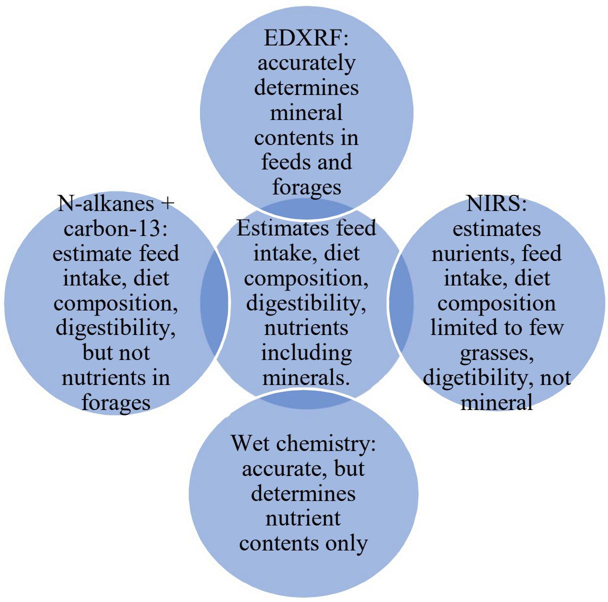

FIG. F-4. Validation of NIRS technology with n-alkanes and their stable carbon isotope data in the mathematical algorithm and incorporation of energy dispersive X-ray fluorescence for mineral analysis provide a complete, mobile solution for feed and forage analysis and animal nutrition evaluation.

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