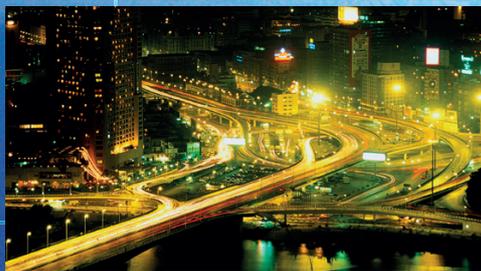


# NUCLEAR TECHNOLOGY REVIEW

2017



60 Years

IAEA *Atoms for Peace and Development*



# Nuclear Technology Review 2017

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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 2017* highlights notable developments in the world in 2016, 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 2017 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. With 448 reactors operating at the end of 2016, nuclear power had a global generating capacity of 391 GW(e), increasing about 8.3 GW(e) since 2015. In 2016, three reactors were permanently shut down, ten new reactors were connected to the grid, and construction started on three reactors. Near and long term growth prospects remained centred on Asia, particularly on China. Of the 61 reactors under construction, 40 were in Asia, as were 47 of the 55 reactors that were connected to the grid since 2005.

2. Thirty countries currently use nuclear power and about the same number are considering, planning or actively working to include it in their energy mix. Of the 30 operating countries, 13 are either constructing new plants or actively completing previously suspended construction projects. Several countries that have decided to introduce nuclear power are at advanced stages of infrastructure preparation.

3. The Agency's 2016 projections for 2030 show that the global nuclear power capacity will expand by between 1.9% in the low and 56% in the high case scenario. Nuclear power, with its proven low-carbon benefits, large capacity and dispatchable output, can contribute significantly to meeting the Paris Agreement goal of limiting global temperature rise well below 2°C above pre-industrial levels and to achieving the United Nations Sustainable Development Goals. Innovative nuclear power technologies could further reduce greenhouse gas emissions and extend the role of nuclear power into new applications.

4. Safety improvements continued to be made at nuclear power plants (NPPs) throughout the world, and the operational safety of NPPs remained high as shown by commonly used safety indicators. The Agency revised its Safety Requirements publications to incorporate the lessons learned from the Fukushima Daiichi accident. Two other Safety Requirements relating to leadership and management for safety and the safety of research reactors were also revised.

5. Low uranium prices continued to constrain companies in their efforts to raise funds for exploration, feasibility studies, the launching of new construction projects and the expansion of existing ones. The 26th edition of the biennial 'Red Book', an authoritative world reference report on uranium, shows that global uranium resources are more than adequate to meet the high case demand scenario mentioned above.

6. Enrichment and other fuel cycle facilities operated at relatively constant levels. Construction of a new storage facility for the IAEA Low Enriched Uranium (LEU) Bank in Kazakhstan started and is proceeding according to schedule.

7. Spent fuel from nuclear reactors in storage amounted to around 273 000 tonnes of heavy metal (t HM) and is accumulating at a rate of around 7000 t HM/year. Five away-from-reactor storage facilities for spent fuel from power reactors came into operation.

8. Considerable decommissioning work around the world is expected in the years to come: 158 nuclear power reactors have been permanently shut down or are undergoing decommissioning. More than 60% of all the operating reactors have been in operation for 30 years or more and about 15% of them are more than 40 years old. Although some may continue to operate longer, many will be retired from service within the next two decades. In addition, more than 480 research reactors and critical assemblies, as well as several hundred other fuel cycle facilities, have been decommissioned or are undergoing decommissioning.

9. Projects on deep geological disposal of radioactive waste continued to be pursued by several countries. Disposal facilities for all other categories of radioactive waste are operational worldwide. Recycling and repatriation options for the management of disused sealed radioactive sources (DSRSs) have been increasing. Borehole disposal projects are at various stages of development in several countries. Successful removal operations brought many DSRSs under proper storage conditions.

10. The Collaborative International Evaluated Library Organization has stimulated advances in the neutron cross section evaluations of nuclides of oxygen, iron, uranium and plutonium isotopes that are particularly relevant to nuclear technologies. The International Network of Nuclear Structure and Decay Data Evaluators' database has received a boost from the Agency's LiveChart of Nuclides website and the Isotope Browser app for nuclear information for use by smart phones.

11. Advances and innovation in accelerator technology included novel pump-probe spectroscopy techniques for in situ investigation of radiation damage, the development of new biocompatible radiation dosimeters, and accelerator-based neutron scattering.

12. About half of the world's 249 research reactors and critical facilities in operation in 56 countries are more than 40 years old. Ageing management, sustainability of fuel supply, options related to spent fuel management, and enhancement of research reactor utilization are the major challenges for the research reactor community. Seven countries are constructing new research reactors, while several others are planning or considering building new ones, as key national facilities for the development of nuclear science and technology infrastructure and programmes, including in the field of nuclear power. Initiatives such as the Agency's Internet Reactor Laboratory project and the ICERR ('IAEA-designated International Centre based on Research Reactor') scheme, as well as regional networks and coalitions, foster international cooperation in the utilization of research reactors for nuclear capacity building.

13. High enriched uranium (HEU) minimization activities, including the return of HEU research reactor fuel to the country of origin, continued. The take-back programmes for HEU fuel of Russian and US origin have achieved commendable results over the years.

14. Despite outages and operational challenges at some facilities, in 2016 there were no major shortages in global supply of molybdenum-99, the most used medical isotope. Major producers continue to progress in their conversion efforts from HEU to LEU-based production.

15. Globalization in the food trade has increased the need for effective food control systems to protect consumers from fraudulently presented food. Food fraud can present a safety risk as a counterfeit product will not have undergone the same controls as a genuine product and its constituents may be unknown. The need for analytical methods to underpin mechanisms for food authentication and traceability has grown rapidly. A range of cost-effective nuclear and related analytical techniques, such as measurement of naturally occurring stable isotopes of the bio-elements in food, can provide information on its geographical origin and production technique. Recent developments in affordable, hand-held, analytical instrumentation are facilitating food authenticity testing at multiple points along the food chain and significantly increasing the effectiveness of control systems.

16. The measurement of the ratios of naturally occurring stable isotopes of the bioelements in foods can often provide information on their geographical origin or production technique, while elemental profiling of foods provides important information on its safety or toxicity and can also help link food to its place of origin. These techniques, in combination with others such as vibrational spectroscopy, DNA analysis and microbial fingerprinting, are proving invaluable for authenticating foodstuffs.

17. Agriculture accounts for approximately two thirds of global freshwater consumption. To achieve the yields required for rising populations, agricultural systems must strive for efficiency. The cosmic ray neutron sensor is a novel device that can capture and quantify soil water content over a large area without the time-consuming and invasive aspects of traditional assessment systems. The soil moisture information provided by this device is leading to better management of increasingly scarce water resources.

18. Genomic tools such as DNA chips help estimate the breeding values of animals at birth. Genome maps pinpoint the location of specific features on the chromosomes and are essential tools for identifying genes and markers responsible for production characteristics and resistance to diseases. Radioisotope techniques can overcome the time consuming conventional genome mapping process in livestock by mimicking genetic recombination events and speeding up the process in vitro.

19. Developing and implementing radiation hybrid maps and genomic tools will help establish breeding programmes for improving the productivity of livestock and enhance food security. High resolution genome maps have been developed for sheep, buffalo, goat and pig and can be developed for a range of other important livestock. The maps have facilitated the development of DNA chips that are widely used to breed cattle for increased milk productivity.

20. Prostate cancer ranks among the three most common cancers in men worldwide and along with lung, liver, stomach and bowel cancers is among the most common causes of cancer death in males. Over half of patients experience biochemical recurrence after a prostatectomy or external beam radiation therapy. Recently, a new molecule that targets the prostate-specific membrane antigen (PSMA), an enzyme associated with prostate cancer cells, has been developed. The PSMA could be an excellent molecular target for the development of radiotracers for PET–CT imaging since it can detect early relapse of disease. Clinical trials are under way.

21. The Agency's Global Network of Isotopes in Precipitation (GNIP) has been recording isotopic ratios of oxygen and hydrogen in precipitation since 1960. GNIP data show that isotopic ratios have large seasonal variations. Recent work at the Agency has shown that there is a substantial correlation between isotope ratios and cloud processes responsible for precipitation. This new knowledge will significantly expand the usefulness of GNIP data for understanding both short-term weather-related, and long-term climate-related processes, and contribute to climate change monitoring and adaptation.

22. Ocean acidification is now measurably affecting many marine organisms, including fish, shellfish, plankton and coral, all critical in different ways to the health and well-being of the oceans and those that depend on them. Experiments using a suite of radioisotopes are addressing how projected decreases in ocean pH will affect such marine organisms, and are enabling new insights into the wide-ranging impacts of ocean acidification. Such information is needed to better anticipate likely effects on our coastal and marine resources in a changing ocean.

23. Radiation techniques can be harnessed to preserve a wide variety of priceless cultural objects. While radiography and computer-assisted tomography techniques assist in detailed examinations of artefacts, radiation treatment helps remove detrimental insect or fungal infestations. Precious articles and documents can be restored and strengthened with the aid of radiation processing technology, which has established a unique niche role in the preservation of the world's cultural heritage.



# Nuclear Technology Review 2017

## Main Report

### A. Power Applications

#### A.1. Nuclear Power Today

1. As of 31 December 2016, there were 448 operational nuclear power reactors worldwide, with a total capacity of 391 GW(e)<sup>1</sup> (see Table A-1). This represents an increase of some 8.3 GW(e) in total capacity, compared to 2015. Of the operational reactors, 82% are light water moderated and cooled, 10.9% are heavy water moderated and cooled, 3.3% are light water cooled and graphite moderated, and 3.1% are gas cooled reactors. Three are liquid metal cooled fast reactors.

2. In 2016, ten new reactors, all pressurized water reactors (PWR), were connected to the grid — the same number as in 2015. Five of these reactors are in China (Changjiang-2, Fangchenggang-2, Fuqing-3, Hongyanhe-4, Ningde-4) and the rest are in India (Kudankulam-2), the Republic of Korea (Shin-Kori-3), Pakistan (CHASNUPP-3), the Russian Federation (Novovoronezh 2-1) and the United States of America (Watts Bar-2).

3. Following the restarts of Sendai-1 and -2 in 2015, which were the first nuclear power reactors to resume full operation in Japan since the Fukushima Daiichi accident, Takahama-3 and -4 restarted operation in January and February 2016, respectively, but were shut down again shortly afterwards. In August 2016, Ikata-3 was restarted. In October 2016, Unit 1 of the Fort Calhoun nuclear power plant (NPP), in the USA, was shut down permanently after 43 years of operation.

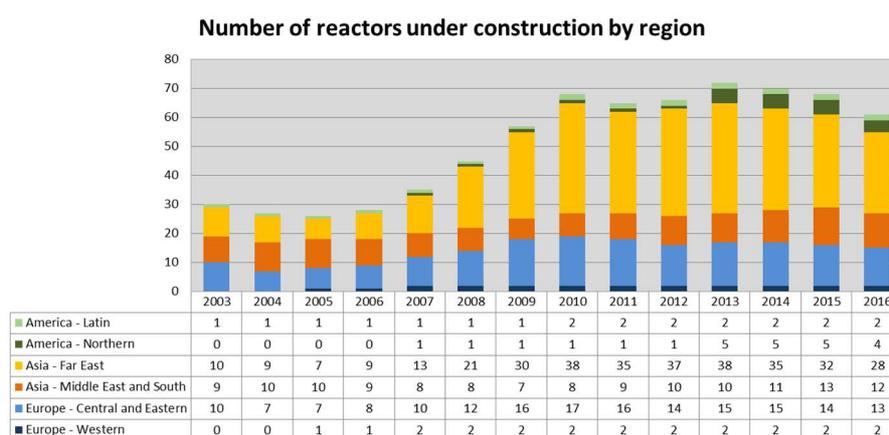


FIG. A-1. Number of reactors under construction by region (Source: IAEA Power Reactor Information System: <http://www.iaea.org/pris>).

4. As of 31 December 2016, 61 reactors were under construction. Expansion as well as near and long term growth prospects remain centred in Asia (Fig. A-1), particularly in China. Of the total

<sup>1</sup> 1 GW(e), or gigawatt (electrical), equals one thousand million watts of electrical power.

number of reactors under construction, 40 are in Asia, as are 47 of the 55 new reactors to 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 2016)<sup>a</sup>*

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2016		Total Operating Experience through 2016	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	3	1 632	1	25	7.7	5.6	79	2
ARMENIA	1	375			2.2	31.4	42	8
BELARUS			2	2 218				
BELGIUM	7	5 913			41.4	51.7	282	7
BRAZIL	2	1 884	1	1 245	15.0	2.9	51	3
BULGARIA	2	1 926			15.1	35.0	161	3
CANADA	19	13 554			95.7	15.6	712	6
CHINA	36	31 384	21	21 622	197.8	3.6	243	2
CZECH REPUBLIC	6	3 930			22.7	29.4	152	10
FINLAND	4	2 764	1	1 600	22.3	33.7	151	4
FRANCE	58	63 130	1	1 630	386.5	72.3	2 106	4
GERMANY	8	10 799			80.1	13.1	824	7
HUNGARY	4	1 889			15.2	51.3	126	2
INDIA	22	6 240	5	2 990	35.0	3.4	460	11
IRAN, ISLAMIC REPUBLIC OF	1	915			5.9	2.1	5	4
JAPAN	42	39 752	2	2 653	17.5	2.2	1 781	5
KOREA, REPUBLIC OF	25	23 077	3	4 020	154.3	30.3	498	11
MEXICO	2	1 552			10.3	6.2	49	11
NETHERLANDS	1	482			3.7	3.4	72	0
PAKISTAN	4	1 005	3	2 343	5.4	4.4	67	11
ROMANIA	2	1 300			10.4	17.1	29	11
RUSSIAN FEDERATION	35	26 111	7	5 520	184.1	17.1	1 226	9
SLOVAKIA	4	1 814	2	880	13.7	54.1	160	7
SLOVENIA	1	688			5.4	35.2	35	3
SOUTH AFRICA	2	1 860			15.2	6.6	64	3
SPAIN	7	7 121			56.1	21.4	322	1
SWEDEN	10	9 740			60.6	40.0	442	6
SWITZERLAND	5	3 333			20.3	34.4	209	11
UKRAINE	15	13 107	2	2 070	76.1	52.3	473	6
UNITED ARAB EMIRATES			4	5 380				
UNITED KINGDOM	15	8 918			65.1	20.4	1 574	7
UNITED STATES OF AMERICA	99	99 869	4	4 468	804.9	19.7	4 210	9
Total <sup>b, c</sup>	448	391 116	61	61 264	2 476.2		16 982	5

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

b. Note: The total figures include the following data from Taiwan, China:

6 units, 5052 MW(e) in operation; 2 units, 2600 MW(e) under construction;

30.5 TW·h of nuclear electricity generation, representing 13.7% 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 Taiwan, China (212 years, 1 month).

### **A.1.1. Newcomers**

5. In the United Arab Emirates, construction continued on all four reactors of the country's first NPP, located at Barakah. Unit 1 is scheduled to start commercial operation in 2017, with the other three to follow suit every following year. An IAEA International Physical Protection Advisory Service mission was completed in November 2016. The Emirates Nuclear Energy Corporation (ENEC) and the Korea Electric Power Corporation signed a joint venture agreement for a long-term cooperation partnership. The United Arab Emirates has sought the Agency's guidance in how research and development can help ensure the sustainability of its nuclear power programme and its relevant institutions.

6. Construction continued on both units of Belarus's first NPP, located at Ostrovet, with commissioning planned for 2019 and 2020. The reactor pressure vessel for Unit 1 was delivered to the site at the end of 2016. An IAEA Integrated Regulatory Review Service (IRRS) mission was conducted in 2016.

7. Bangladesh signed an engineering, procurement and construction contract with Atomstroyexport of the Russian Federation in December 2015. In July 2016, a site licence was issued and an intergovernmental credit agreement was concluded with the Russian Federation. Unit 1 of the Rooppur NPP is expected to be commissioned in 2023 and Unit 2 in 2024.

8. Egypt signed a project development agreement with the State Atomic Energy Corporation "Rosatom" of the Russian Federation in February 2015 for the construction of a new NPP at El Dabaa, and has since signed a further financial intergovernmental agreement with the Russian Federation. The completion of the first unit on the El Dabaa site is scheduled for 2025 and of the other three units by 2027. Jordan has established an International Advisory Group to review the progress in implementing the country's nuclear programme, and has hired consultants to lead the preparation of the investment decision, planned for 2018. In November 2016, Viet Nam's National Assembly endorsed the Government's decision to cancel the country's nuclear power plans. The National Assembly had originally approved plans in 2009 for the construction of two NPPs with a combined capacity of 4000 megawatts.

9. The "newcomer" countries that are considering, planning or actively working to include nuclear power in their energy mix have been working with the Agency in developing the necessary nuclear infrastructure. As these countries take their sovereign decisions to opt for nuclear, they engage with supplier countries to build their future nuclear power plants. The Agency, with a specific methodology embedded in its Milestones Approach, plays an important role in the establishment of safe, secure and sustainable programmes. The Agency assists those Member States through peer review and expert missions, training courses and modelling tools that systematically cover the 19 nuclear infrastructure issues of the Milestones Approach. With two Integrated Nuclear Infrastructure Review (INIR) missions and two follow-up missions conducted in 2016, the total number of INIR missions deployed since its launch in 2009 had reached 21 in 15 Member States.

### **A.1.2. Expanding countries**

10. The US Nuclear Regulatory Commission (NRC) has issued a 40-year operating licence to the Tennessee Valley Authority for Watts Bar Unit 2, which was connected to the grid in June and started commercial operation in October 2016. The Watts Bar site is the first to comply with the NRC's Fukushima-related orders on accident mitigation strategies. The construction of Watts Bar Unit 2 was 80% complete when it was stopped in the 1980s — developing this existing asset saved time and cost relative to alternatives for new baseload capacity.

11. The Hinkley Point C project for construction of a 3200 MW(e) NPP with two EPR reactors in Somerset, England, was approved by the Électricité de France (EDF) Board of Directors in July 2016, and by the UK Government, with some new conditions attached regarding the investment, in September 2016. The plant has a projected lifetime of 60 years. EDF expects the first reactor to become operational in early 2026, about ten years after the investment decision and the governmental approval.

12. There were three construction starts in 2016: KANUPP-3 in Pakistan, and Tianwan-6 and Fangchenggang-4 in China.

### A.1.3. Operating countries

13. Of the 450 operational nuclear power reactors, 293 have been in service for 30 years or more. When a reactor reaches the end of its design life, it undergoes a safety review and an ageing assessment of its essential structures, systems and components for validating or renewing its licence to operate for terms beyond the originally intended service period. In recent years, a number of nuclear power reactors with valid operating licences, or those that could have received operating licence extensions, were selected for earlier shutdown by owners/operators, with economic factors cited as the primary reason in many cases.

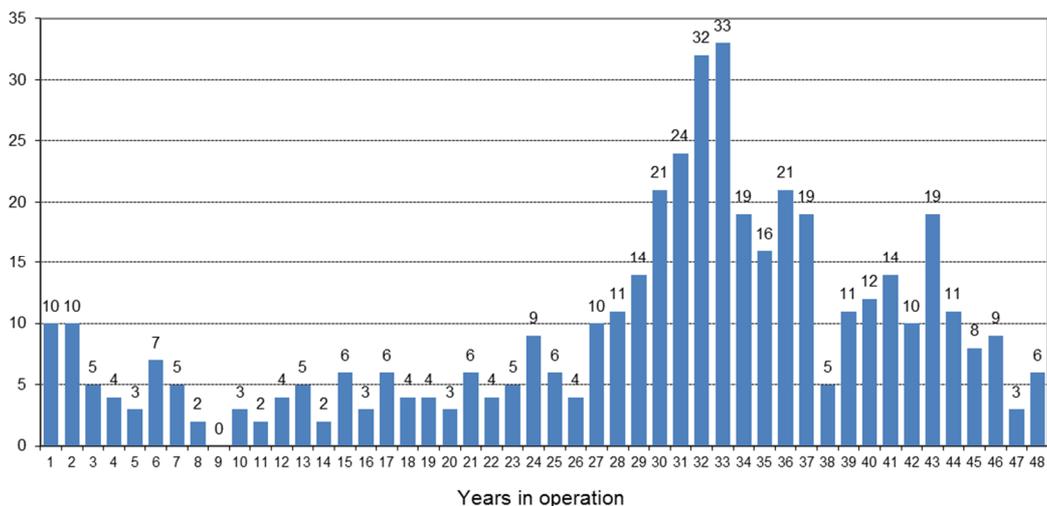


FIG. A-2. Distribution of operational power reactors by age, as of 31 December 2016 (Source: IAEA Power Reactor Information System: [www.iaea.org/pris](http://www.iaea.org/pris)).

14. By 2040, half of all the operating NPPs in the USA are likely to have been operating for 60 years, if their operating licences get extended by the NRC from their original 40-year design life. Several utilities are considering extending their plants' operating lifetimes by another 20 years, requiring a second licence renewal for the additional years of operation. Exelon's Peach Bottom Atomic Power Station in Pennsylvania and Dominion's Surry Power Station in Virginia are the first NPPs in the USA that will pursue a second licence renewal for operation for a total of 80 years.

15. Switzerland's nuclear power phase-out policy, which suggested a constitutional limit of 45 years on the operational lifetime of NPPs, was rejected by a referendum held on 20 November 2016. About 33% of Swiss electricity was generated from nuclear power in 2015.

## A.2. The Projected Growth of Nuclear Power

16. Nuclear power is expected to continue expanding globally in the coming years, even as the pace of growth would slow down, in the short run, as a result of competition from low fossil fuel prices and renewable energy sources. According to the Agency's 2016 projections (Fig. A-3), taking as basis the 382.9 GW(e) installed capacity at the end of 2015, the global nuclear power capacity would reach 598 GW(e) by 2030, increasing by 56% in the high case scenario. In the low case scenario, however, the world nuclear capacity in 2030 will expand by 1.9% to 390 GW(e). The actual new capacity added in the next 14 years will be much more than the net increase in global nuclear capacity, considering the replacement of many nuclear power reactors that are being retired. In the low case scenario, about 150 GW(e) of new capacity will be added, while in the high case scenario this figure would rise to 300 GW(e). Extending these projections to 2050, the nuclear capacity will grow to 898 GW(e) in the high case scenario, while it would be approximately the same as the present level in the low case scenario.

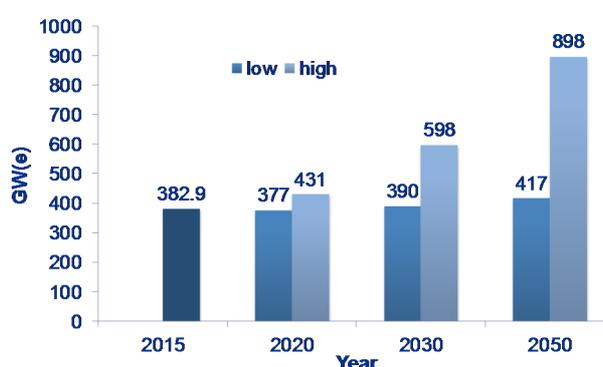


FIG. A-3. Projections for world nuclear capacity (Source: *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, IAEA Reference Data Series No. 1, 2016*).

17. These projections are prepared by an expert group convened every year by the Agency and are derived from aggregating country-by-country assessments. The experts review all operating reactors, possible licence extensions, planned shutdowns and plausible construction projects foreseen for the next few decades. They are neither intended to be predictive nor to reflect the full range of possible future scenarios from the lowest to the highest feasible cases. Despite the considerable uncertainties in these projections, the high case scenarios of the IAEA, the International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD), and the World Nuclear Association (WNA) all show a possible increase of 600–700 GW(e) by 2030 in global nuclear power capacity (Fig. A-4).

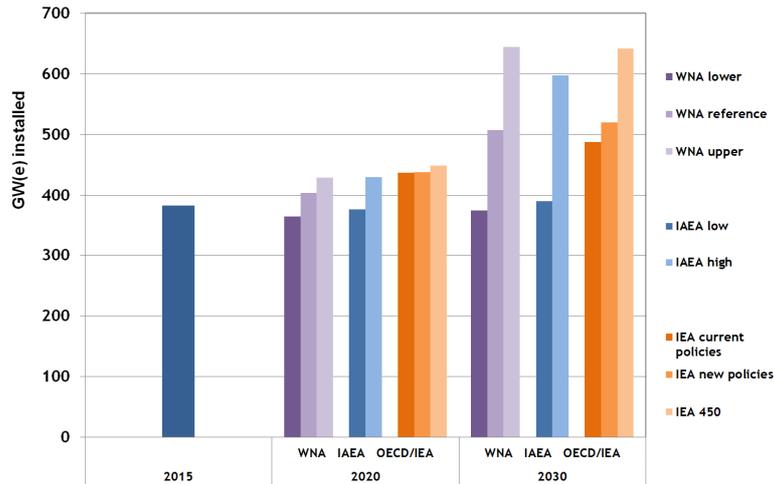


FIG. A-4. Comparison of the IAEA's latest projection for nuclear power capacity with the OECD/IEA's 2016 scenarios and the WNA's projections (OECD/IEA figures are based on gross capacity).

18. With the entry into force of the Paris Agreement on 4 November 2016, the Parties are now required to prepare, communicate and maintain successive nationally determined contributions that they intend to achieve in order to hold the increase in global temperature well below 2°C above pre-industrial levels<sup>2</sup>. The Paris Agreement provides the framework for incrementally increasing climate mitigation efforts until the 2°C goal has been achieved. This is necessary, as current national mitigation plans fall substantially short of meeting the 2°C goal.<sup>3</sup>

19. Nuclear power can contribute significantly to meeting the 2°C goal and to achieving the United Nations Sustainable Development Goals<sup>4</sup> because of its proven low-carbon benefits, large capacity and dispatchable output.<sup>5</sup> However, fully tapping the potential of nuclear power requires significant expansion, matching the high case projections mentioned above (reaching 898 GW(e) by 2050). Achieving these capacities is challenging because existing plants need upgrades and life extensions to allow continued operations, retiring nuclear capacity has to be replaced, and a wave of new builds is needed to support the growing energy demands of developing economies. Investments at this rate are not unprecedented, but will likely require governmental support, new contractual arrangements to reduce investor risks, and a price on carbon emissions that will improve the economics of low carbon alternatives such as nuclear power.

20. Innovation was named in the Paris Agreement as key to meeting the 2°C goal. Innovative nuclear power technologies, including evolutionary designs, small and medium sized or modular reactors (SMRs) and advanced fuel cycles could more efficiently contribute to reducing greenhouse gas emissions and extending the role of nuclear power into new applications. For example, nuclear power can further reduce carbon emissions by supplying process heat to industrial processes and it can also be used to produce desalinated water for cities in dry climates. However more investment in research, development and demonstration is needed.

<sup>2</sup> The Paris Agreement is available at [http://unfccc.int/paris\\_agreement/items/9485.php](http://unfccc.int/paris_agreement/items/9485.php)

<sup>3</sup> The Agency booklet *Climate Change and Nuclear Power 2016* is available at <http://www-pub.iaea.org/books/IAEABooks/11090/Climate-Change-and-Nuclear-Power-2016>.

<sup>4</sup> More information on *United Nations Sustainable Development Goals* are available at <https://sustainabledevelopment.un.org/sdgs>

<sup>5</sup> The Agency publication *Nuclear Power and Sustainable Development* (2016) is available at <http://www-pub.iaea.org/books/IAEABooks/11084/Nuclear-Power-and-Sustainable-Development>.

## A.3. Fuel Cycle

### A.3.1. Front end

#### Uranium resources and production

21. The 26th edition of the biennial joint publication of the OECD Nuclear Energy Agency and the IAEA, *Uranium 2016: Resources, Production and Demand*, also known as the ‘Red Book’, was issued in November 2016<sup>6</sup>. A key finding of this report is that currently defined identified resources recoverable at a cost of less than \$130/kgU are more than adequate to meet the high case demand scenarios that were mentioned earlier. The main challenges are the investment and expertise that will be required to bring these resources into production. This is exacerbated by the current depressed uranium market. Projected production capacity, which is higher than the existing and committed production capacities, is adequate to meet the high case demand scenario. Existing and committed production capacities are sufficient to meet the low case demand scenario.

22. Uranium spot prices have not been this low since 2004. They stayed within the range of \$75/kg U to \$42/kg U in 2016. Reduced prices considerably restricted the ability of companies to raise funds for exploration, feasibility studies and development of new expansion projects.

23. Many uranium projects remained on hold or with low financial implications while testing and additional studies were being conducted, and some projects that had been opened, or that had reached advanced stages of construction, were placed on care and maintenance. In 2015, 60 496 tonnes of uranium metal (t U) was produced, the highest in the last decade, up from 56 041 t U in 2014 and higher than the 59 331 t U produced in 2013.

24. Kazakhstan remains the world’s leading uranium producer. Coming almost entirely from its in situ leach mines, production rapidly increased between 2000 and 2012, while recent increases have been modest, with production of 24 455 t U expected for 2016 and a similar figure predicted for 2017.

25. The annual production capacity of Cigar Lake in Canada (the world’s highest grade uranium mine that began commercial production in May 2015) is currently 5000 t U/year and is expected to increase to 6900 t U/year by 2018. With encouraging uranium exploration results continuing to be reported from the Athabasca Basin, Canada maintained its position as the second biggest world producer.

26. Commissioning of the newly-constructed Husab uranium mine in Namibia continued in 2016 and the point of initial production was reached, with the rate expected to ramp over 24 months to 2018. The full capacity could be 5770 t U/year, with a likely lifetime of over 20 years. Namibia’s Rössing and Langer Heinrich uranium mines continued operations over 2016. Low-key feasibility work continued at some of the other Namibian uranium deposits.

27. In Australia, the Four Mile in situ leach uranium mine continued to operate with an annual capacity of approximately 1000 t U/year in full production mode. At the Ranger project, the operator, Energy Resources of Australia, continued to process its ore stockpiles to meet sales obligations and is progressing with the rehabilitation of parts of the site no longer in operation. Production during 2016 was less than 2500 t U, compared to 4000 to 6000 t U/year between 1997 and 2009. Under current arrangements, mining and processing must cease by January 2020 and rehabilitation needs to be finalized within a further five years. The operators of the Olympic Dam copper–uranium–gold–silver mine continued conventional operations whilst further testing of the option of heap leaching a portion of its ore was carried out. Advances were made in studies on, and the approval processes for, several

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<sup>6</sup> *Uranium 2016: Resources, Production and Demand* is available at <http://www.oecd-nea.org/ndd/pubs/2016/7301-uranium-2016.pdf>

uranium deposits in Western Australia, but no firm construction and opening dates have been announced.

28. Further progress was made with feasibility studies and approvals for the rare earth, base metals and uranium project at the Kvanefjeld deposit in Greenland, Kingdom of Denmark. The Eighth Mineral Resource Assessment Workshop to evaluate the nation's potential uranium resources was held in Copenhagen, in November 2016.

29. China continued its uranium exploration activities and increased development expenditures both nationally and abroad. A significant increase (over 100%) in inferred resources has been reported recently and is the result of intensified exploration activities in several sedimentary basins within the country. Development expenditures abroad continued to be significant (amounting to over \$1.5 billion during 2014 and 2015), primarily due to development of the Husab mine in Namibia.

30. Historically, a significant proportion of identified uranium resources are never brought into production for technical, social or political reasons. As part of efforts to enhance the security of international and domestic supply, Argentina and the USA have a number of active projects that seek to evaluate undiscovered uranium resources. The Agency continued to collaborate with major players to bring such evaluation techniques to other Member States via training workshops and publications, including the above-mentioned Copenhagen workshop.

### **Conversion and enrichment**

31. Canada, China, France, the Russian Federation, the United Kingdom and the USA operate commercial scale conversion plants. Commercial enrichment services are carried out by five companies: the China National Nuclear Corporation (China), AREVA (France), the State Atomic Energy Corporation "Rosatom" (Russian Federation), USEC (USA) and URENCO (both Europe and the USA). Small conversion and enrichment facilities are in operation in Argentina, Brazil, India, the Islamic Republic of Iran, Japan and Pakistan.

32. The UK-based design, engineering and project management consultancy Atkins has been selected by the US Department of Energy (DOE), along with joint venture partners Westinghouse and Fluor Corporation, to operate the depleted uranium hexafluoride (DUF6) conversion facilities at the DOE's Paducah Gaseous Diffusion Plant, in Kentucky, and the Portsmouth Gaseous Diffusion Plant in Piketon, Ohio. The joint venture, registered under the name Mid-America Conversion Services, will operate the two facilities to convert DOE's inventory of approximately 765 000 t of stored DUF6, a co-product of the uranium enrichment process, to depleted uranium oxide for possible future reuse, storage or disposal.

33. The US-based Centrus Energy Corporation has signed a contract with UT-Battelle, the operator of the DOE's Oak Ridge National Laboratory, for further work towards commercial-scale uranium enrichment using the company's 'American Centrifuge' technology. In early 2016, Centrus completed a successful three-year demonstration of a full, 120-machine cascade of advanced centrifuges at its facility in Piketon, Ohio, which confirmed the machines' long-term performance and reliability under real operating conditions. Centrus is continuing to explore technology refinements and other ways to deploy the most cost-effective commercial enrichment capacity, taking advantage of the current period of time when capacity expansion is not needed in the market.

### **Fuel fabrication**

34. In January 2016, Lightbridge, a US nuclear fuel development company, received the final regulatory approval for testing its newly developed metallic fuel in Norway's Halden research reactor (irradiation is expected to begin in 2017). Lightbridge's advanced metallic fuel is made of zirconium-uranium alloy and uses a unique composition and fuel rod geometry, which, as the company claims, enables it to operate at a higher power density than currently used uranium oxide

fuels. Later, in July 2016, Lightbridge received from the European Patent Office the approval for a key patent covering its metallic nuclear fuel rod design.

35. In January 2016, Westinghouse Electric Company announced that its Springfields nuclear fuel fabrication facility in the UK had met the requirements necessary for manufacturing fuel assemblies suitable for the Westinghouse SMR design. In February 2016, the Czech national utility ČEZ awarded Westinghouse a contract to supply six lead test assemblies for its Temelín NPP, which consists of two Russian-designed WWER-1000 units.

36. In March 2016, China North Nuclear Fuel Company (CNNFC), a subsidiary of China National Nuclear Corporation, launched a pilot line at its Baotou plant for producing fuel elements for China's High Temperature Reactor–Pebble-Bed Module, a high temperature gas cooled reactor demonstration power plant in Shidaowan. The Baotou plant also produced a prototype fuel assembly for China's CAP1400 pressurized water reactor design, the performance of which is now being verified. In May 2016, CNNFC completed its first production line of AP1000 fuel, two months after China's National Nuclear Safety Administration had given its approval for feeding uranium into the 400 tU/year production line. CNNFC will manufacture two sets of dummy assemblies before beginning full production.

37. In April 2016, Westinghouse Electric Company announced the expansion of its nuclear fuel factory in Västerås, Sweden. The US-based firm, which is majority-owned by Japan's Toshiba, explained that the expansion was in response to growing demand for nuclear fuel supply diversification for WWER-1000 reactors in Europe.

38. In May 2016, Global Nuclear Fuel – Americas (GNF-A) agreed with Russian nuclear fuel company TVEL (a subsidiary of the State Atomic Energy Corporation “Rosatom”) to produce TVS Kvadrat fuel in the USA for Westinghouse pressurized water reactors (PWRs). As part of a consortium, GNF-A will manage the project in the USA, focusing on licensing and quality assurance, as well as providing engineering services, whereas TVEL will provide design expertise and technical support, and will undertake the fabrication of the first batches of assemblies for pilot production programmes. TVEL also signed a contract in December 2016 with Swedish utility Vattenfall, becoming the third company, after AREVA and Westinghouse, to supply fuel for units 3 and 4 of the Ringhals NPP.

39. In June 2016, Indústrias Nucleares do Brasil signed a contract with Argentine State company CONUAR to export enriched uranium. The agreement will see the export of four tonnes of uranium dioxide powder for use in the first fuel load for Argentina's CAREM modular reactor.

40. In June 2016, the Machine Building Plant (MSZ), a TVEL subsidiary based in Elektrostal, Russian Federation, completed acceptance tests for fuel pellets for the UK's Sizewell B NPP, a single-unit PWR plant that accounts for 3% of the UK's total electricity demand. MSZ also completed acceptance tests of components for its ETVS-14 and ETVS-15 experimental fuel assemblies with dense mixed uranium–plutonium nitride fuel (that will be assembled at the Siberian Chemical Complex) for pilot operation in the BN-600 fast reactor unit at the Beloyarsk NPP and in the future lead-cooled BREST-OD-300 reactor.

41. Also in June 2016, three experimental fuel assemblies with REMIX (‘regenerated mixture’) fuel were loaded into Unit 3 of the Russian Balakovo NPP during a scheduled maintenance outage. REMIX fuel is produced from a non-separated mixture of uranium and plutonium (produced by the reprocessing of used fuel), doped with a small quantity of enriched uranium. Each experimental fuel assembly consists of six fuel rods with REMIX fuel along with standard uranium fuel rods. The REMIX fuel will stay in Balakovo-3 for at least two fuel cycles (about three years) and irradiated assemblies will then be sent for post-irradiation examinations. REMIX fuel technology will help the

Russian Federation achieve a closed nuclear fuel cycle and minimize the volume of radioactive waste it produces.

42. In June 2016, Japan's Fukuoka High Court upheld a March 2015 ruling by the Saga District Court that mixed oxide (MOX) fuel could be used at Unit 3 (off-line since 2010) of the Kyushu Electric Power Company's Genkai NPP, the restart of which has been under review by the Nuclear Regulation Authority. The Shikoku Electric Power Company restarted commercial operation of Unit 3 of the Ikata NPP, partly using MOX fuel, in September 2016.

43. In October 2016, Lightbridge and France's AREVA NP signed an agreement for a US-based 50/50 joint venture to develop, manufacture and commercialize fuel assemblies for most types of light water reactors, including PWRs, boiling water reactors, SMRs, and research reactors.

44. Also in July 2016, the Novosibirsk Chemical Concentrates Plant, part of TVEL, started producing the new generation of TVS-2M nuclear fuel for Unit 3 of the Tianwan NPP in China, which is under construction and planned to be commissioned in 2018. With a higher burnup, this fuel allows for longer periods of operation between two refuelling outages.

45. In August 2016, Ukraine's National Nuclear Energy Generating Company "Energoatom" signed a contract with European uranium enrichment company URENCO. Under the contract, URENCO will supply Westinghouse's fabrication facility in Västerås, Sweden, with enriched uranium for producing nuclear fuel for Energoatom.

46. Japan's Kansai Electric Power Company announced on 30 August 2016 that AREVA had started fabricating at its Melox facility, in France, 16 MOX fuel assemblies for Unit 4 of the Takahama NPP.

47. In September 2016, the Ulba Metallurgical Plant (UMP), a subsidiary of Kazakhstan's national uranium production company Kazatomprom, and CGNPC Uranium Resources Company, a subsidiary of the China General Nuclear Power Corporation (CGNPC), signed an agreement for setting up a fuel assembly production plant with a capacity of 200 tonnes per year, based on the UMP's existing facility, to supply fuel pellets to Chinese nuclear power reactors.

48. A notable development in the field of pressurized heavy water reactor fuel technology is that Argentina's National Atomic Energy Commission has recently successfully completed a 1500-hour endurance test at a high pressure loop for the verification of a new design of fuel for the Atucha-2 NPP with different spacer grids. The main objectives of the new design are to simplify the fuel manufacturing process and to reduce its cost.

### **A.3.2. Assurance of supply**

49. In December 2010, the Agency's Board of Governors adopted resolution GOV/2010/70 whereby it approved the establishment of the IAEA Low Enriched Uranium (LEU) Bank as set out in document GOV/2010/67. In June 2015, the Board of Governors approved a host state agreement for the IAEA LEU Bank between the Agency and Kazakhstan and in December 2015 the Agency and Kazakhstan completed the basic legal framework to establish the IAEA LEU Bank at the UMP site in Ust-Kamenogorsk. Since then, the Agency and Kazakhstan have been progressing with the implementation of the project.

50. In January 2016, Kazakhstan enacted the Law on the Use of Atomic Energy. Following the adoption of this new law, an upgrade of the regulatory framework was initiated, with a number of regulations already enacted and some in the final stage of review. A feasibility study concluded that construction of a new storage facility for the IAEA LEU Bank, rather than upgrading an existing facility, was both more cost-effective and would provide for simplified and robust security

arrangements, as well as enhanced safety features incorporated into its design. An Agency mission team visited UMP in March 2016 to assess progress of work related to the design of the new storage facility and concluded that the design provides adequate measures to ensure nuclear safety and security. Construction of the new storage facility started in summer 2016 and Kazakhstan expects that the storage facility will be commissioned and ready to receive LEU in the second half of 2017. The Agency has now started activities in preparation for acquisition of the LEU to be stored at the IAEA LEU Bank. A Cylinder Management Programme that will ensure the long term safety and security of the cylinders in situ, as well as during subsequent transport, without the need for periodic decanting of LEU from the cylinders is being finalized.

51. 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**

52. The duration of storage is often extended to beyond the originally licensed life of storage facilities, or even beyond their design life. The importance of ageing management has become a priority in recent years as a result of the long timeline necessary to develop advanced recycling solutions or to establish final disposal facilities. This is especially the situation in States where dry storage systems were deployed for relatively short term use.

53. In order to ensure continued safety, guidance on ageing management and supporting research and development (R&D) projects are being developed, particularly in Germany and the USA. For example, the NRC has been developing a *Managing Aging Processes in Storage (MAPS) Report*, issued for comment in September 2016, to assist independent fuel storage facility operators with licence renewals. To develop the technical basis and methodology for the guidance to be provided to Member States, the Agency also launched in October 2016 a coordinated research project on ageing management programmes for spent fuel dry storage systems.

54. The amount of spent fuel in storage is estimated to have reached 273 000 tonnes of heavy metal (t HM) by the end of 2016 and is accumulating at a rate of around 7000 t HM/year.<sup>7</sup> During 2016, five more away-from-reactor (AFR) spent fuel storage facilities came into operation. All five facilities are dry and use concrete cask technology. They are located at Ignalina (Lithuania), Palo Verde (Mexico), Sizewell (UK), Watts Bar (USA) and Summer (USA). The global distribution of 151 AFR storage facilities operating in 27 countries is provided in Figure A-5. The USA, which now has 70 dry storage facilities accommodating around 36% of its total spent fuel inventory, continues to add new dry storage facilities on an annual basis. Current projections suggest that there will be 74 independent dry spent fuel storage facilities in the USA by 2020.

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<sup>7</sup> Worldwide, about 10 000 t HM of spent fuel is discharged from NPPs every year.

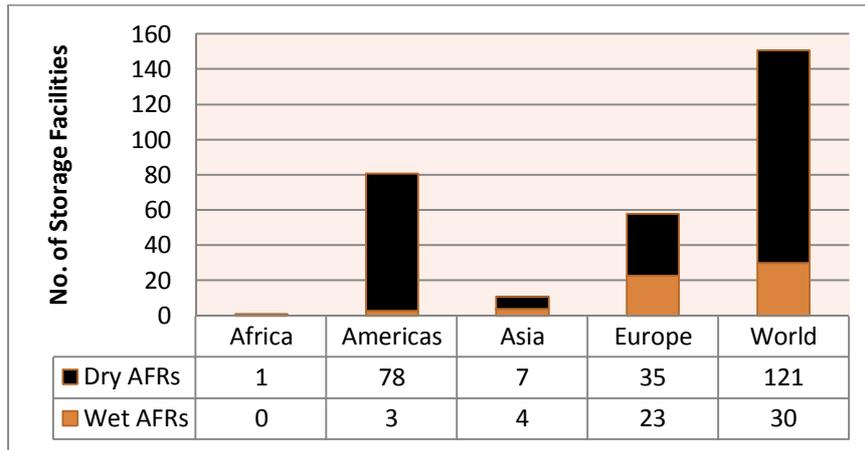


FIG. A-5. Global distribution of AFR spent fuel storage facilities.

55. There have been delays in implementing new AFR storage facilities in Japan, Spain and Ukraine due to a variety of reasons. One of these projects, the Mutsu AFR storage facility in Japan, is now expected to become operational in 2019.

56. In 2016, preparations started for the defuelling of the Wylfa NPP in the United Kingdom after the last operational reactor was shut down on 30 December 2015. Dating from the 1970s, the Wylfa NPP has the oldest operational spent fuel dry stores for power reactor fuel. The target is to defuel the reactor cores and the associated dry stores before the end of 2018. The UK Department for Business, Energy and Industrial Strategy has launched a new British nuclear research and innovation programme. The initial phase of this programme, funded with £20 million (\$25 million) from 2016 to 2018, covers five major themes: advanced fuels, materials and manufacture, reactor design, advanced recycling, and a strategic toolkit. This represents the Government's wider commitments to double the UK's energy innovation spending, expected to reach over £40 million (\$50 million) per year by 2021.

57. The Russian Federation has established a new programme for the management of its spent nuclear fuel, for the period '2016–2018 and up to 2020', to replace the previous programme that has expired. It covers transportation of spent nuclear fuel materials from Russian NPPs either to the Mayak reprocessing plant in Ozersk, or to the centralized interim storage facilities of the Mining and Chemical Complex (MCC) in Zheleznogorsk, for subsequent reprocessing. The MCC site has water pools that can be used for the future storage of spent nuclear fuel from the WWER-1000 reactors of the Balakovo, Kalinin, Novovoronezh and Rostov NPPs, as well as from the Beloyarsk BN-600 fast reactor. The MCC site also features, since 2012, a centralized dry interim storage facility for up to 8129 tonnes of Russian spent nuclear fuel from the RBMK-1000 reactors of the Leningrad, Kursk and Smolensk NPPs. The Mayak reprocessing plant has increased its reprocessing productivity by 35%. In 2016, it received for the first time spent nuclear fuel from the Leningrad NPP's RBMK-1000 reactor. It has also started reprocessing the spent uranium–zirconium fuel from Soviet and Russian icebreakers that has accumulated for decades in storage facilities.

58. Lithuania has built, next to its shutdown Ignalina NPP, an Interim Spent Fuel Storage Facility to store the spent nuclear fuel unloaded from Units 1 and 2 of the plant. The storage capacity consists of about 190 reinforced concrete casks, which have space for around 17 000 fuel assemblies that will be stored for 50 years. Having completed cold testing in June 2016, the facility is in an advanced stage of commissioning.

59. Financial difficulties and land allotment issues in the exclusion zone of the Chernobyl NPP are the main factors that have led to the project for construction of Ukraine's Central Spent Fuel Storage Facility being delayed until the end of 2018.

60. The preliminary work on the site selection for a new nuclear fuel reprocessing plant in Lianyungang, in Jiangsu Province, China has been suspended due to public acceptance issues. However, the construction plans remain in place, since five other Chinese provinces are under consideration for this project.

### A.3.4. Decommissioning, environmental remediation and radioactive waste management

#### Decommissioning of nuclear facilities

61. Across the world, 158 power reactors have been shut down or are undergoing decommissioning, including 17 that have been fully decommissioned. More than 150 fuel cycle facilities have been permanently shut down or are undergoing decommissioning and 127 have been fully decommissioned. There are also over 180 research reactors that have been shut down or are undergoing decommissioning. Over 300 research reactors and critical assemblies have been fully decommissioned.

62. During 2016, innovative approaches were deployed at the Dungeness A NPP in the UK, such as the use of divers to clean up former cooling ponds. Continuous support is being provided by further R&D work, mainly in countries with long-running nuclear power programmes, such as Belgium, France, Japan, the Russian Federation, Spain, the UK and the USA. A recent example is the RACE ('Remote Applications in Challenging Environments') initiative in the UK, which formally started in May 2016.

63. Decommissioning of NPPs after an accident is a specific and difficult issue that a few countries are currently having to deal with. Notable progress was achieved in Japan with preparations for the decommissioning of the Fukushima Daiichi NPP (see the box below for further details). Another example of post-accident activities is the completion, after several years of construction work and with support provided by international donors, of the New Safe Confinement over Unit 4 of the Chernobyl NPP in Ukraine.



*FIG. A-6. The New Safe Confinement over Unit 4 of the Chernobyl NPP (left, view from the construction site; right, view from Unit 3). The structure is 108 metres high, 162 metres long and 257 metres wide, and weighs about 36 000 tonnes. (Photos: Chernobyl NPP)*

64. The implementation of decommissioning projects is also continuing in Bulgaria, Lithuania and Slovakia, where NPPs were shut down before the end of their design lives and financial support is being provided through the European Bank for Reconstruction and Development.



FIG. A-7. Dismantling activities at turbine halls of Units 1 (left) and 2 (right) of Lithuania's Ignalina NPP (Photos: Ignalina NPP).

### Progress in the decommissioning of the Fukushima Daiichi nuclear power plant

Four of the six reactors at the Fukushima Daiichi NPP experienced core damage and/or hydrogen explosions. Decommissioning of these reactors is an unprecedented project which is being conducted within the framework of the Mid-and-Long-Term Roadmap<sup>8</sup> and Technical Strategic Plan<sup>9</sup> adopted by the Japanese authorities. At a side event of the 60th regular session of the Agency's General Conference in September 2016, representatives from Japan highlighted the progress made and presented plans to address, with the cooperation of the international community, challenges such as fuel debris retrieval.

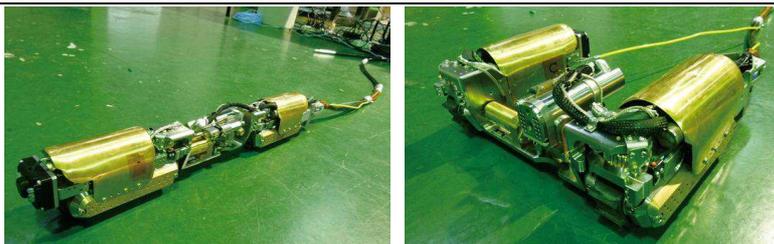
One major issue is the contaminated water, which is generated by the groundwater flowing into reactor buildings and mixing with the coolant used to cool fuel debris. The contaminated water is treated using a nuclide removal system. As part of the efforts to keep water away from contaminated sources, freezing pipes have been installed for the landside impermeable walls to block groundwater, and partial freezing of the walls started in March 2016. In order to prevent the leakage of contaminated water, the seaside impermeable walls were closed in October 2015.

The 1535 fuel assemblies that were stored in the pool of Unit 4 were completely removed in 2014. In preparation for the removal of fuel assemblies from Unit 1 (392 fuel assemblies), Unit 2 (615 fuel assemblies) and Unit 3 (566 fuel assemblies), work on decontaminating and shielding the operating floors has been initiated to achieve greater reduction in radiation dose.

Muon tomography and robotics have been used to survey the internal conditions of the primary containment vessels (PCVs) of the reactor units. A robot inspecting inside the PCV of Unit 1 confirmed that there are no major damages to the equipment such as primary loop recirculation pumps, and that wide areas at the bottom of the drywell are covered by sediments. From the muon tomography carried out in Unit 2, a shadow of high density substance has been identified at the bottom of the reactor pressure vessel, which seems to be the fuel debris.

<sup>8</sup> *Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station*, issued by the Inter-Ministerial Council for Contaminated Water and Decommissioning Issues on 12 June 2015, is available at [http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20150725\\_01b.pdf](http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20150725_01b.pdf).

<sup>9</sup> A summary of the *Technical Strategic Plan 2016 for Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc.*, issued by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation on 13 July 2016, is available at [http://www.dd.ndf.go.jp/en/strategic-plan/book/20160926\\_SP2016esum.pdf](http://www.dd.ndf.go.jp/en/strategic-plan/book/20160926_SP2016esum.pdf).



*FIG. A-8. A shape-changing robot used to inspect the interior of the PCV of Unit 1 (Photos: International Research Institute for Nuclear Decommissioning, Japan).*

Intensive decontamination work is being carried out to improve the on-site environment. With an additional effective dose inside the site boundary of less than 1 mSv/year, it is no longer necessary to wear full-face masks or protective clothes in about 90% of the site.

The Decommissioning R&D Partnership Council was established by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation in order to enhance R&D through the promotion of collaboration with the relevant institutions. A new global R&D organization based in Japan called the Collaborative Laboratories for Advanced Decommissioning Science was established by the Japan Atomic Energy Agency (JAEA). Additionally, the JAEA began operation of the Naraha Remote Technology Development Center, where the development and verification tests for the remote operation equipment, such as robots, and for the associated processes will be carried out. The JAEA also initiated construction of the Okuma Analysis and Research Center.

### **Management of disused sealed radioactive sources**

65. 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.

66. A number of successful operations have been conducted in 2016 to remove DSRs from user premises and bring them under control in proper storage conditions. French-manufactured Category 1 DSRs were successfully repatriated from Lebanon and Tunisia (one source in each case), with a further two sources repatriated from Cameroon. One Category 1 DSR was removed from a teletherapy head in Uganda and transferred to safe and secure storage. Two Category 1 DSRs were removed from a hospital and placed into safe and secure storage in Jordan. Removals of Category 1 and 2 sources have been initiated in several Member States, including Albania, Burkina Faso, Lebanon and the former Yugoslav Republic of Macedonia, with the work expected to be completed in 2017.

67. Significant progress was made in incorporating a mobile hot cell into various borehole disposal designs, which will minimize the handling of sources and eliminate unnecessary transport. In addition, a mobile toolkit has been designed to facilitate conditioning operations on Category 3–5 DSRs and to support preparation for borehole disposal.

68. Operations involving the conditioning of DSRs were completed in Indonesia, Malaysia, Nepal, the Philippines, Thailand and Viet Nam, and local personnel in these countries received appropriate training.

69. The Agency extended access to the International Catalogue of Sealed Radioactive Sources and Devices to a larger group of users from Member States, thereby facilitating the identification of DSRs found in the field. Efforts to add more details on sources and devices were initiated in 2016, to further improve the usefulness of the catalogue.

70. The operation to remove high activity DSRs from Brazil began in October 2016 and is scheduled to finish in February 2017. Under a trilateral cooperation agreement between Brazil, Canada and the USA, more than 80 Category 1 and 2 DSRs of Canadian and US origin will be processed and shipped overseas. The former group will be sent to the company Gamma-Service Recycling in Leipzig, Germany, for recycling, whereas the latter will be repatriated to the USA. This operation will be performed by trained teams from the South African Nuclear Energy Corporation.

### **Radioactive waste predisposal**

71. Argentina has initiated the start-up of a facility at the Ezeiza Atomic Centre for the cementation and compaction of low level waste coming from the National Atomic Energy Commission (mainly from research reactor operation, radioisotope production and research activities) and other external generators (used in fuel fabrication and in medical, industrial and research applications).

72. A licence for full operation of Fortum's solidification facility at the Loviisa NPP was granted by Finland's Radiation and Nuclear Safety Authority. The facility will treat the existing and future low and intermediate liquid waste (including ion exchange resins and sludges) generated by plant operations. This facility is a good example of how integrated waste management planning leads to a single facility that is designed to manage effectively legacies from the past, waste from current operations and future waste inventories.

73. Minimization of waste is a key goal at Fukushima Daiichi where large amounts of solid waste items such as protective clothing (gloves, protective suits) and operational waste (paper, plastic, rags, wood) are generated on a daily basis. Consequently, the Tokyo Electric Power Company has recently commissioned a miscellaneous solid waste incineration facility comprising two lines, each with a processing capacity of 300 kilograms of waste per hour. The resulting ash is a small fraction of the original volume and will be stored in drums on-site awaiting disposal.

74. Australia has completed the design of a full-scale integrated plant to treat the waste from its molybdenum-99 production facility, using 'synroc' technology. Construction is due to start in 2017. The synroc process takes liquid radioactive waste and immobilizes it into a durable 'synthetic rock' matrix for disposal.

75. An in-container vitrification (ICV) plant has been commissioned at the Sellafield plant in the UK. Vitrification is an established technology to immobilize liquids and sludges into a durable glass waste form suitable for disposal. The GeoMelt ICV system is designed to treat smaller volume problematic waste streams for which there is currently no disposal path.

76. Sellafield Ltd (UK) announced in March 2016 that it had transferred the entire bulk stocks of historic nuclear fuel from its Pile Fuel Storage Pond to a modern storage building. This reduced the radioactivity levels at the 68-year-old spent fuel pond by 70%, significantly reducing risks to people and the environment.

### **Radioactive waste disposal**

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

78. Further disposal facilities for LILW, such as in Belgium (Dessel), Bulgaria (Radiana), Canada (Kincardine), Germany (Konrad), the Islamic Republic of Iran (Talmesi), Lithuania (Stabatiškės), Romania (Saligny) and Slovenia (Vrbina) are at different stages of licensing or construction.

79. 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.

80. In Australia, the Government of South Australia received the report from its Nuclear Fuel Cycle Royal Commission and announced that it would pursue nine of its twelve recommendations. This includes pursuing continued investigation to assess the opportunity to establish storage and disposal facilities of international used nuclear fuel and intermediate level waste in South Australia.

81. Bulgaria's Radioactive Waste State Enterprise received a licence and started constructing a near surface disposal facility for LLW at the Radiana site, near the Kozloduy NPP.

82. In Canada, a federal government decision is expected in late 2017 on the environmental assessment for Ontario Power Generation's proposed deep geological repository for LILW at the Bruce site in Kincardine, Ontario. Also, an environmental assessment was initiated for Canadian Nuclear Laboratories' proposal to establish a near surface disposal facility for low level radioactive waste and other suitable waste at the Chalk River site.

83. In China, the development of the deep geological disposal programme progressed with the decision to construct an underground research facility (URF) in a crystalline formation in the Beishan area. Site investigations and iterative site selection in a sedimentary host formation have been carried out there.

84. The Estonian Government decided in March 2016 that the country's future disposal facility would be co-sited with the current central storage facility, at the Paldiski submarine centre.

85. In Finland, construction work on the world's first spent nuclear fuel geological disposal facility in Olkiluoto started in December 2016.

86. Upon request by the French Nuclear Safety Authority, the Agency conducted in November 2016 a peer review of the Safety Options File of the Cigéo high level waste geological disposal project.

87. The German Government received the report from its national commission for the storage of highly radioactive waste, which recommended a national siting process for a deep geological repository. Detailed recommendations are included on what safety relevant exclusion criteria and criteria for comparative assessments should be considered, as well as what stakeholder engagement processes should be established to achieve broad public acceptance of siting decisions. The Government also received a report on the cost estimation and funding for the national back-end liabilities, including for radioactive waste disposal.

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

89. The Republic of Korea established its national policy on the management of high level waste, based on the recommendations of its Public Engagement Commission on Spent Nuclear Fuel Management. It presents a timeline for developing a geological disposal programme, including siting an underground research laboratory and the construction and operation of a geological disposal

facility. The second stage of the Wolsong LILW disposal facility, which envisages the construction of near surface disposal vaults, is currently under licence review.

90. The Russian Federation is progressing with its strategy to implement a network of near surface disposal facilities throughout the country. The National Operator for Radioactive Waste Management has obtained two licences for near surface disposal at an existing nuclear site in the Ural region, while further pursuing disposal licence applications at two other existing nuclear sites. A licence application for a URF, as the first part of the planned future deep geological disposal facility near Krasnoyarsk, is also under evaluation.

91. In June 2016, the Swedish Radiation Safety Authority endorsed the licence application for the spent fuel deep geological repository, and a further main hearing is expected to take place in 2017. The licensing process for the extension of the repository for short-lived LILW, known as the Final Repository for Short-lived Radioactive Waste, is still ongoing.

92. Switzerland has progressed with the second stage of its deep geological repository siting process. This involved actively engaging with the 'Regional Conferences' of stakeholders from the siting regions, concluding its 3D seismic site characterization campaign, and obtaining drilling licences for its borehole-based site characterization programme. Comparative assessments are based on 13 criteria and 49 indicators as provided by the national safety authority.

93. In July 2016, the planning authority in Cumbria, United Kingdom, approved the construction of two new vaults at the UK's Low Level Waste Repository, along with an extension to a third vault. This ensures the future of the facility, near the village of Drigg, until 2050. Construction work is expected to start in 2017.

#### **A.4. Safety**

94. Progress continues to be made in strengthening and improving safety at NPPs throughout the world. This included identifying and applying lessons learned from the Fukushima Daiichi accident, improving the effectiveness of defence in depth, strengthening emergency preparedness and response capabilities, maintaining and enhancing capacity building, and protecting people and the environment from ionizing radiation.

95. The Agency has defined nuclear safety priorities to strengthen the global nuclear safety framework. These nuclear safety priorities cover the full range of the Agency's activities in nuclear, radiation, transport and waste safety. The Agency published revised Safety Requirements in the IAEA Safety Standards Series to take account of the lessons learned from the Fukushima Daiichi accident. These publications include five Safety Requirements applicable to NPPs which were issued as focussed revisions 'by amendment'. In addition, full revisions of two other Safety Requirements relating to leadership and management for safety and the safety of research reactors were issued. The review and revision of the related Safety Guides have continued<sup>10</sup>.

96. Analysis of data from the International Reporting System for Operating Experience for nuclear power plants indicates a number of ongoing challenges, including vulnerabilities in the plant design or operating practices during some external hazard situations, and with the implementation of plant modifications. The data also indicate that contractor surveillance continues to be a challenge and that the number of incidents related to component degradation due to ageing is increasing.

97. An increasing number of nuclear power reactors around the world are implementing long term operation (LTO) and ageing management programmes. At the end of 2016, 46% of the 450 nuclear

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<sup>10</sup> See IAEA Nuclear Safety Review 2017 (GOV/2017/3) for details.

power reactors operating in the world had been in operation for between 30 and 40 years, and another 15% for more than 40 years.

98. The International Nuclear Safety Group (INSAG) noted that modern reactor designs are being developed to reduce the risks from internal events to very low levels. The predominant source of risk is likely to arise from external events, which justifies continuing attention in the years ahead. Experts attending Agency Technical Meetings continue to express an interest in addressing lessons arising from the Fukushima Daiichi accident related to: (a) the uncertainties associated with the evaluation of extreme hazards; (b) the need for using historical and prehistoric data in the evaluation of external hazards; (c) consideration of external hazard combinations; (d) consideration of the impact of external hazards on multi-unit sites; and (e) the use of probabilistic approaches to the analysis of external events.

99. The operational safety of NPPs remains high, as indicated by safety indicators collected by the Agency and the World Association of Nuclear Operators. Figure A-9 shows the number of unplanned manual and automatic scrams or shutdowns per 7000 hours (approximately one year) of operation per unit. Scrams are just one of several possible indicators of safety performance, but this approach is commonly used as an indication of success in improving plant safety by reducing the number of undesirable and unplanned thermal hydraulic and reactivity transients requiring reactor scrams.

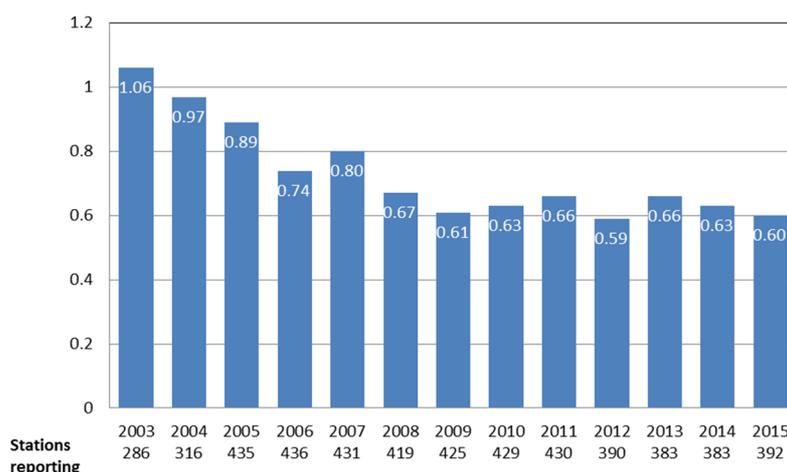


FIG. A-9. Mean rate of scrams: the number of automatic and manual scrams that occur per 7000 hours of operation of a unit (Source: IAEA Power Reactor Information System: [www.iaea.org/pris](http://www.iaea.org/pris)).

100. Several Member States are experiencing population doses from medical uses of radiation that exceed those from natural background radiation and those from other human sources. With increased peaceful uses of radiation technology, the number of Member States in such position is expected to grow. A significant percentage (20–50% in some areas) of individual medical exposures can be avoided with more appropriate selection of medical procedures and effective radiation protection measures. The established approaches for the optimization of radiation protection of patients in diagnostic imaging have been only partly implemented globally, and continuous efforts are needed for their wider and proper use for improving safety and quality.

101. Complex radiotherapeutic technologies and procedures are increasingly being introduced into regions where they have not been previously used, resulting in the need to establish adequate safety measures. While there is broad agreement among experts that radiotherapy is an effective form of treatment, it is also recognized that safety measures need to be further enhanced.

## B. Atomic and Nuclear Data

102. The Collaborative International Evaluated Library Organization (CIELO), coordinated by the OECD Nuclear Energy Agency (OECD/NEA), has stimulated advances in the neutron cross section evaluations of nuclides that are particularly relevant to nuclear technologies: oxygen, iron, uranium and plutonium isotopes. The benefits of a CIELO-coordinated effort between experts in nuclear science from around the world have led to improved accuracy of large-scale nuclear criticality and neutron transport simulations. CIELO evaluations are considered as candidates for inclusion in the world nuclear data libraries, such as the Evaluated Nuclear Data File library ENDF/B-VIII (USA), the Japanese Evaluated Neutron Data Library, the Joint Evaluated Fission and Fusion library (OECD/NEA), the Chinese Evaluated Nuclear Data Library, and the TALYS-based Evaluated Nuclear Data Library (European Commission/IAEA).

103. The International Network of Nuclear Structure and Decay Data Evaluators (NSDD) is a worldwide collaborative initiative to assemble and evaluate the basic structure and decay properties of nuclides. The use of the NSDD database by nuclear scientists has recently been given a large boost following its coupling with modern communication technology such as the LiveChart of Nuclides website at the Agency, and the Isotope Browser app, which was launched by the Agency in 2013. This freely available app for Android and iPhone operating systems enables retrieval of nuclide information on a mobile device and has already been downloaded about 40 000 times.

104. The EXFOR ('Experimental Nuclear Reaction Data') database now contains more than 22 000 experimental nuclear reaction datasets from 1935 to the present day. This unique database lies at the basis of nuclear data libraries that are used for all nuclear technologies, primarily for NPP analysis, fuel cycle issues, innovative reactor designs, fusion and medical isotope production. New collaborative partnerships, especially in China and India, have been established to bring the database up to date.

105. Physics at entirely different scales of magnitude are currently being bridged by an innovative nuclear data approach to the analysis of radiation damage. With the help of current computer power it is now possible to estimate damage response functions — such as the NRT<sup>11</sup> and arc- ('athermal recombination-corrected') displacements per atom (dpa) and replacements per atom standards, as well as kerma (kinetic energy released in matter) and gas production — on a better scientific basis, including a quantitative expression of the uncertainties. These developments will have consequences for the shielding of fission and fusion reactors, as well as of accelerators.

106. There has been a notable increase in activities and publications in the field of medical isotope production using accelerators, and in the related use of charged-particle induced nuclear data libraries for establishing the most optimal production routes for such medical isotopes.

107. Uncertainty propagation of basic nuclear and atomic data to large-scale nuclear devices is currently extended from the traditional field of criticality to other aspects of safe and reliable nuclear operation. Notable research fields where uncertainty estimates are now taken into account include the evaluation of radiation damage for fission and fusion reactors, the use of atomic and molecular data for state-resolved modelling of hydrogen and helium in fusion plasma, and obtaining data on erosion and tritium retention in beryllium plasma-facing materials.

108. The International Conference on Nuclear Data for Science and Technology was jointly held by the European Commission's Joint Research Centre (JRC), the OECD/NEA and the IAEA in Bruges,

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<sup>11</sup> The NRT-dpa standard is a measure for damage in a material and was proposed by Norgett, Robinson and Torrens in 1975.

Belgium, in September 2016, and was attended by about 450 participants. The latest developments in nuclear data technology were presented, such as the experimental possibilities at the JRC's Institute for Reference Materials and Measurements in Geel, Belgium, and more systematic approaches to nuclear data production using the TALYS code.

109. Improved nuclear data have been developed for alpha-induced reactions on fluorine, which is of relevance for safeguards analyses.

110. China is investing more effort in the evaluation of nuclear data for a molten salt reactor (MSR). Various experimental and modelling activities, coordinated by the China Nuclear Data Center in Beijing, are now targeted towards MSR relevant data, which have an impact on safety and economy.

111. The European Commission is investing in nuclear data development over a broad scale via its CHANDA ('Solving Challenges in Nuclear Data') project, with laboratories, universities and research laboratories from almost all European Union countries collaborating on nuclear data development. The emphasis is on minimization of radioactive waste and on fast neutron systems. The development of new nuclear data libraries will result in superior computational analyses of advanced reactor systems.

## **C. Accelerator and Research Reactor Applications**

### **C.1. Accelerators**

112. Particle accelerators were developed to shed light on fundamental questions posed by scientists investigating the inner structure and properties of the atomic nucleus and the physical laws that govern the interactions of radiation with matter. Nowadays, the worldwide application of tens of thousands of accelerators in industry, medicine, the environment and basic research including subatomic physics and astrophysics, benefits millions of people in their day-to-day lives. To respond to the ever increasing demand for accelerators in cutting-edge scientific research and to sustain and extend the broad range of applications with strong socio-economic benefits, it is vital to further improve and advance accelerator technology. Technological innovations are pushing accelerators to their limits in terms of the energy, type and size of the accelerated particle beams. A further challenge is to reduce the size and cost of accelerators for industrial and medical applications.

### C.1.1. Novel pump-probe techniques developed for in situ investigation of radiation damage

113. Our understanding of radiation effects is advanced by experimentation and simulations. An exciting development is the rapid emergence of pump-probe techniques where short, intense ion pulses (from induction accelerators such as NDCX-II at Lawrence Berkeley National Laboratory or from laser-plasma accelerators) can induce changes in structural dynamics in materials that can then be tracked in-situ with fast structural probes, e.g. ultra-fast electron diffraction or intense X-ray pulses. These new techniques enable the investigation of ion radiation effects in-situ. This advances our fundamental understanding and can accelerate the development of novel materials with enhanced performance and radiation hardness in high radiation environments.



FIG. C-1. The NDCX-II accelerator<sup>12</sup> at the Lawrence Berkeley National Laboratory, Berkeley, USA, enables the study of structural dynamics in materials. The photograph shows the ten-metre long accelerator with the target end station in the foreground (Photo: Berkeley Lab).

### C.1.2. New bio-compatible radiation dosimeters using focused ion beams

114. The characteristics of radiation dosimeters fabricated from synthetic diamond offer some advantages over more traditional devices, including radiation hardness and biocompatibility, especially as used in proton therapy. Focused ion beams over a wide range of proton energies of 5-250 MeV are being utilized to evaluate the suitability of single crystal diamond devices as accurate dosimeters. The high energy beams correspond to clinical practice and the low energy beams, provided by a scanning nuclear microprobe system, allow the detailed response of the device to be measured so that new detector designs can be evaluated. Images made using the ion beam induced charge (IBIC) technique with a 5.5 MeV microbeam allow the detailed response of the device to be measured along with the charge collection efficiency, which can approach 100%.

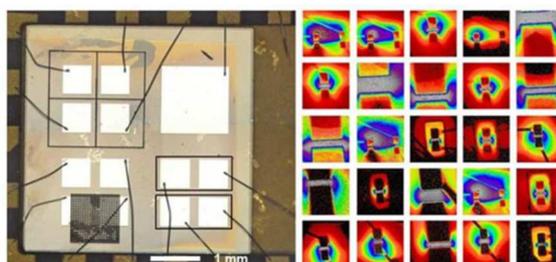


FIG. C-2. The images show an array of prototype dosimeters fabricated from synthetic device grade diamond and a montage of maps of the radiation response of the different designs measured by the IBIC technique using 5.5 MeV He<sup>+</sup> ion irradiation. (Photos: Prof. D.Jamieson, University of Melbourne; Dr J.Davis, University of Wollongong; and Dr D.Prokopovich, ANSTO)

<sup>12</sup> For further details please see P.A. Seidl, et al., Nucl. Inst. Methods A800 (2015) 98–103.

### C.1.3. Accelerator-based neutron scattering

115. Led by developments in proton accelerators, within the last decade, the time-averaged flux of neutrons from spallation sources, such as the Spallation Neutron Source, USA, and the forthcoming European Spallation Source, Sweden, have exceeded those of the highest flux beam reactors. The unprecedented brightness of these sources, coupled with the penetrating nature of the neutron and its strong scattering by hydrogen and magnetic moments, promises advances in energy and magnetic materials, life sciences, archaeology and geology, and engineering materials.

116. For such applications, neutrons must be moderated, and traditionally this has been done within bulky cryogenic moderators, from which only a small fraction of neutrons were emitted towards experimental facilities. Focus is therefore being placed on a new generation of moderator materials and designs. By selecting one of the spin isomers of hydrogen, parahydrogen, rod- or pancake-shaped liquid cold moderators can be built. These designs reduce neutron absorption and spectrometers can be placed more efficiently around the source. Similarly, solid methane is a very efficient cold moderator, but susceptible to radiation damage. Therefore, new solid moderator materials and designs are being examined. Accurate knowledge of the neutron cross sections of candidate materials is required, and the necessary measurements are being performed at many research accelerators, including in Argentina, Japan, South Africa and the USA. Prototype designs in which pellets of these new materials can be blown into the vessel, later removed, and regenerated are being developed, e.g. in the Russian Federation, as another way of dealing with radiation damage.



FIG. C-3. The European Spallation Source site in Lund, Sweden, as of October 2016. Fed by a pulsed 2 GeV proton linac delivering 5 MW average beam power, the world's most powerful neutron source is to start up in 2019 (Source: [https://dam.esss.lu.se/asset-bank/images/assets/33/40\\_2S5D41851.jpg](https://dam.esss.lu.se/asset-bank/images/assets/33/40_2S5D41851.jpg)).

## C.2. Research Reactors

117. 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.

118. According to the Agency's Research Reactor Database, 774 research reactors have been built in 70 countries, and, as of 31 December 2016, 249 of these were operating in 56 countries. The Russian Federation has the highest number (55) of research reactors that are operational or under temporary shutdown, followed by the USA (42), China (17) and Japan (14). Many developing countries also have operating research reactors, including 10 facilities in Africa. Worldwide, 64 research reactors operate at power levels higher than 5 MW and thus offer high neutron fluxes for various products and services.

Table C-1. Common applications of research reactors around the world<sup>13</sup>.

Type of application <sup>a</sup>	Number of research reactors involved <sup>b</sup>	Number of Member States hosting such facilities
Teaching/training	165	51
Neutron activation analysis	118	51
Radioisotope production	87	43
Neutron radiography	69	37
Material/fuel irradiation	68	27
Neutron scattering	45	30
Geochronology	27	23
Transmutation (silicon doping)	24	16
Transmutation (gemstones)	17	10
Neutron therapy, mainly R&D	16	11
Other <sup>c</sup>	120	36

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

<sup>b</sup> Out of 249 research reactors considered (230 operational, 19 temporarily shut down), as of 31 December 2016.

<sup>c</sup> Other applications include calibration and testing of instrumentation, shielding experiments, nuclear data measurements, public visits and seminars

119. Many operating research reactors still have a relatively low utilization factor, and half of them are over 40 years old. The majority of them require continuous attention in the areas of strategic planning, ageing management, modernization and refurbishment. Efforts to enhance utilization and yield additional revenues continue to grow. In the past three years, the operating organizations of 41 research reactor facilities prepared and submitted strategic plans to the Agency for review<sup>14</sup>.

120. International collaboration continues to promote and enhance the utilization of research reactors for nuclear capacity building, including education and training, among other areas. One example is the Internet Reactor Laboratory (IRL) project, which was launched in 2015, with host reactors in both Latin America and the Caribbean and Europe. The project seeks to connect, via the Internet, universities and research institutes with operating research reactors dedicated to education and training. Implementation of the IRL project continued in 2016, with six live transmissions in Latin America and the Caribbean (with Argentina's CNEA RA-6 reactor as the host facility and recipient organizations in Colombia, Cuba and Ecuador) and five live transmissions in Europe and Africa (with the French Alternative Energies and Atomic Energy Commission (CEA) ISIS reactor as the host facility and recipient organizations in Belarus, Lithuania, Tunisia and the United Republic of Tanzania). Another example is the ICERR ('IAEA-designated International Centre based on Research Reactor') scheme, facilitated by the Agency and aimed at promoting cooperation among Member States for nuclear capacity building and collaborative R&D activities. Following on from the designation of the first ICERR in 2015 — namely, the CEA, represented by its Saclay and Cadarache research centres — the Research Institute of Atomic Reactors in Dimitrovgrad, Russian Federation,

<sup>13</sup> Based on data from the Agency's Research Reactor Database: <http://nucleus.iaea.org/RRDB/>.

<sup>14</sup> The Agency revised its guidance document from 2001 entitled *Strategic planning for research reactors: Guidance for reactor managers* (IAEA-TECDOC-1212) by including aspects of new research reactor or major refurbishment projects, and sharing experiences from well-operated facilities through numerous examples. The revised version is due for publication as IAEA Nuclear Energy Series No. NG-T-3.16 in 2017.

was designated as an ICERR in 2016 and the Belgian Nuclear Research Centre (Mol, Belgium) became a candidate for such designation.



*FIG. C-4. Left: A live demonstration experiment is transmitted to the Tanzania Atomic Energy Commission from the host reactor, the CEA's ISIS research reactor in Saclay (France), during a coordination meeting of the Agency's regional technical cooperation project RAF/1/005 (Photo: IAEA). Right: Live transmission of a laboratory from the host reactor CNEA RA-6 in Bariloche, Argentina (Photo: National Atomic Energy Commission CNEA).*

121. Several countries are building new research reactors as key national facilities for the development of nuclear science and technology infrastructure and programmes, including nuclear power. Construction of new research reactors is ongoing in Argentina, Brazil, France, India, the Republic of Korea, the Russian Federation and Saudi Arabia. Several Member States, including Belarus, Belgium, the Plurinational State of Bolivia, the Netherlands, the USA and Viet Nam, have formal plans to build new research reactors. Others, such as Azerbaijan, Bangladesh, Ethiopia, Ghana, Kenya, Kuwait, Lebanon, Malaysia, Mongolia, Myanmar, Nigeria, the Philippines, Senegal, South Africa, the Sudan, Tajikistan, Thailand, Tunisia and the United Republic of Tanzania, are considering building such facilities.<sup>15</sup> In 2016, the commissioning of the Jordan Research and Training Reactor, a 5 MW(th) multipurpose research reactor located on the campus of the Jordan University of Science and Technology, was successfully completed.

122. The research reactor regional networks and coalitions facilitated by the Agency<sup>16</sup> help foster international cooperation and enable research reactors to expand their stakeholder and user communities. In 2016, two research reactor organizations, the Australian Nuclear Science and Technology Organisation (ANSTO) and the Reactor Institute Delft in the Netherlands, were designated as IAEA Collaborating Centres in the areas of multi-analytical techniques for materials research, environmental studies and industrial applications, and neutron-activation and neutron-beam based methodologies for research reactors, respectively.

123. By the end of 2016, 97 research reactors had been converted to LEU fuel or confirmed as permanently shut down, including one molybdenum-99 production facility that used HEU. Important achievements in 2016 were the conversion to LEU fuel of the Chinese miniature neutron source reactor (MNSR) prototype, which reached criticality in March, and of the WWR-K reactor in Kazakhstan, which reached criticality in April, and the removal of all HEU from the Fast Critical Assembly in Japan. The Agency, together with China, the USA and other stakeholder countries,

<sup>15</sup> The Agency publication *Specific Considerations and Milestones for a Research Reactor Project* (IAEA Nuclear Energy Series No. NP-T-5.1) and a set of supporting documents aim to help Member States in this area.

<sup>16</sup> The Agency supports several different research reactor coalitions in the Baltic, the Caribbean, central Africa, Central Asia, Eastern Europe, the Mediterranean region, as well as in the Commonwealth of Independent States and global TRIGA research reactor networks. In the last case the Agency has recently released *History, Development and Future of TRIGA Research Reactors* (Technical Reports Series No. 482, IAEA, Vienna, 2016).

continued to support Ghana in its efforts to convert and remove the HEU core of its MNSR, which is expected to occur in 2017. Activities supporting the conversion of the Nigerian MNSR were initiated.

124. Activities related to HEU minimization include the return of HEU research reactor fuel to the country of origin where it was enriched. By the end of 2016, the removal of nearly 1300 kg of fresh and spent HEU research reactor fuel had been completed under the take-back programme for US-origin HEU fuel. Under the take-back programme for Russian-origin HEU fuel, 2228 kg of fresh and spent HEU research reactor fuel was removed in the same period. In September 2016, Poland, the USA, the Russian Federation and the Agency returned to the Russian Federation the last remaining 61 kg of Russian-origin HEU materials from the Maria research reactor in Otwock-Świerk, Poland.

125. Advanced uranium–molybdenum fuels are required for the conversion of high flux, high performance research reactors. Although substantial progress in this field has been made, further work on irradiation testing, post-irradiation examination, and manufacturing techniques, is necessary to achieve commercial availability for qualified high-density LEU fuels.

126. While there were no major shortages of molybdenum-99 in 2016, operational challenges at processing facilities continue. The outages of some global facilities in 2016 did not result in any shortages. Belgium’s BR2 research reactor, a major irradiator for molybdenum-99 production, restarted on 19 July 2016 after a nine-month shutdown for extended maintenance and modernization activities. Canada’s National Research Universal reactor ceased the production of molybdenum-99 on 31 October 2016, but remains on ‘hot standby’ to serve as a backup production capacity in the unlikely event of a global shortage between 1 November 2016 and 31 March 2018. The other major producers have been increasing their production to compensate for this loss.

127. The conversion of molybdenum-99 production processes from HEU to LEU continues, with ANSTO (Australia) and the company NTP Radioisotopes (South Africa) leading the supply of LEU-based molybdenum-99. In 2016, ANSTO made significant progress on its new production facility, the construction of which is expected to be completed in early 2017. NTP Radioisotopes is continuing to convert its processes to the exclusive use of LEU. Two other major producers, the Institute for Radioelements in Belgium and Mallinckrodt in the Netherlands, continue to make progress in supporting the conversion of their commercial-scale production processes from HEU to LEU.

## **D. Food and Agriculture**

### **D.1. Nuclear and Related Techniques to Determine Food Authenticity**

128. Food quality and safety are major concerns for both the food industry and consumers. Recurrent food authenticity and safety crises can endanger public health and provoke loss of public confidence in the integrity of the food supply. Globalization in the food trade has increased the need for effective food control systems to protect consumers from contaminated and fraudulently presented food. Food crime — intentional mislabelling or adulteration of food commodities on an organized and large scale for financial gain — has become a major criminal activity which can result in substantial economic losses and discredit entire economic sectors, leading to barriers to international trade. Although food fraud is driven by financial gain, there is often a food safety risk, since the adulterant or counterfeit product will not have undergone the same controls as a genuine product and its constituents may be unknown. Examples include the addition of melamine to milk powder to increase apparent protein content, which caused many thousands of illnesses and several infant deaths due to the toxicity of

melamine; the adulteration of high quality extra virgin olive oil with cheaper oils such as groundnut oil, which are undeclared on the label and may cause serious allergic reactions; and even counterfeit rice made from potato starch and industrial synthetic resin.

### **D.1.1. Analytical techniques**

129. The need for analytical methods to underpin mechanisms for food authentication and traceability has grown rapidly, and is likely to increase in the future with the increasing complexity of food supply chains and advances in food processing and technology. Nuclear techniques provide key attributes required for food authenticity testing.

130. The measurement of the ratios of naturally occurring stable isotopes of the bioelements (hydrogen, carbon, nitrogen, oxygen and sulphur) in food can often provide information on their geographical origin or production technique through linkages to the ratios of the isotopes found in the environment or in the production process. Heavy element (e.g. strontium) stable isotopes can also provide information related to the geology of the area of origin, and this ‘signature’ is transferred through soils to plants and animals. Because stable isotopes are intrinsic characteristics of the atoms in the food, their distribution and ratios are difficult to manipulate for fraudulent ends.

131. Elemental profiling of food provides important information on its safety with regard to the concentration of potentially toxic elements and can provide information that links food to its place of production. The multi-element composition of animal tissues reflects, to some extent, that of the vegetation that they eat. For example, alkaline metals, especially rubidium and caesium, being easily mobilized in the soil and easily transported into plants, are good indicators of geographical identity.

132. Metabolomic fingerprinting, the analysis of metabolites which are the result of cellular or molecular processes in an organism, is also used for authenticity testing. Metabolomics can be either targeted, focusing on groups of related metabolites to provide direct functional information for modelling, or untargeted, detecting patterns in the metabolome that can differentiate between sample sets and can be used to build models for classification of unknown samples. An example is spin-generated fingerprint profiling using proton nuclear magnetic resonance (NMR) spectroscopy to screen fruit juices and wines.

133. These techniques, in combination with others such as vibrational spectroscopy, DNA analysis and microbial fingerprinting, are proving invaluable for authenticating foodstuffs.

134. The successful application of such techniques requires research on their application for different food commodities, the development of extensive databases of measurement results from authentic foodstuffs, and robust statistical analysis and modelling.

### **Accessible authenticity testing techniques**

135. Recent developments in analytical instrumentation are making the required analytical techniques more accessible. Some instruments that were previously used only in the laboratory are becoming available in more affordable benchtop, portable or hand-held versions, which may be able to provide a screening capability. For example, relatively affordable benchtop NMR instruments have recently become available that can perform screening analyses previously run on expensive high-field NMR instruments that require specialized infrastructure and dedicated personnel. Similarly, hand-held X-ray fluorescence and near-infrared spectrometers are now commercially available and finding applications in food testing. Other benchtop or portable techniques that have potential applications for authenticity testing include ion-mobility spectrometry, which employs a nickel-63 ionization source and has recently become widely used to screen for explosives and drugs in airports, and isotope ratio measurement by laser ablation molecular isotopic spectrometry.

136. The cost-effectiveness and accessibility of the modern techniques means that they could be used to screen foods at multiple points along the food chain by stakeholders in the food industry, regulators and consumers, which would significantly increase the effectiveness of control systems. If required, suspect products could then be tested using high-end confirmatory techniques at a reference laboratory to provide more detailed information for follow-up investigations.

## **D.2. Cosmic Ray Neutron Sensor: A New Method for Area-wide Soil Moisture Monitoring**

137. Agriculture accounts for approximately two thirds of global freshwater consumption. To help meet the challenges of global climate change and rapidly increasing population numbers, agricultural communities around the world must maximize yields while improving the efficiency of water use through irrigation. Achieving this will require methods for monitoring soil water resources to increase the efficiency of irrigation water application. Traditional methods of measuring soil water content (SWC) involve point-based in situ devices that relay SWC information representative of the point at which they are placed. This kind of in situ sensing is often incapable of capturing area-wide information on SWC, including on its natural heterogeneity, without a network of point-based devices. The cosmic-ray neutron sensor (CRNS) is a novel device capable of capturing and quantifying area-wide SWC information remotely over a large spatial area (a circle of approximately 250 m in radius or 20 ha in area), without the time-consuming and invasive aspects of traditional point-based SWC networks. Communities can benefit from soil moisture information at the scale provided by the CRNS leading to better management of increasingly scarce water resources.

138. The CRNS method relies on the detection of incoming high-energy nuclear particles from the cosmos into the atmosphere. Many of these particles will collide with gases in the atmosphere, whereby they lose energy and undergo a cascade of transformations into less energetic particles that ultimately become neutrons near the soil surface (Fig. D-1). These neutrons are readily absorbed by hydrogen atoms. This means that the presence of hydrogen in the environment is the primary means by which incoming neutrons disappear from the soil and atmosphere. This is true for all forms of hydrogen in a given environment, whether these sources of hydrogen change quickly (soil moisture), or slowly (vegetation, surface water, or soil organic material, or does not change over time (water in clay minerals or human structures). The CRNS passively detects these neutrons as they move through the soil and air and determines the counts of neutrons per unit time. Because the majority of hydrogen in and on the Earth's surface occurs in the form of water, a relationship can be established between the counts of neutrons and the amount of water present in the soil of any given area. A calibration process is included in the CRNS methodology intended to remove the signal of environmental hydrogen other than SWC. This process is undertaken through in-situ validation sampling campaigns.

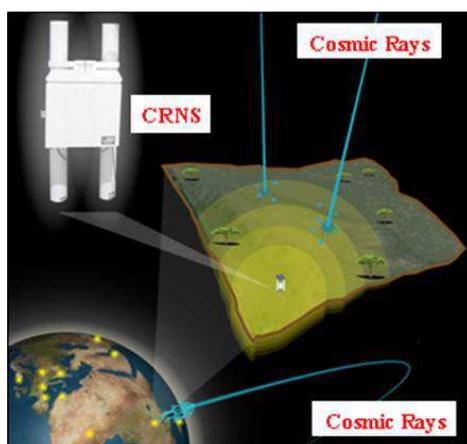


FIG. D-1. Illustration of incoming cosmic rays interacting with the atmosphere, leading to neutrons at the soil surface that can be measured by the CRNS at the landscape level. (Photo: IAEA)

139. The use of the CRNS technique as a fixed stationary soil water monitoring tool within agricultural settings has been well established in Member States around the world<sup>17</sup>. While this method has great capacity for generating area-wide soil moisture information<sup>18</sup>, the sensor response to natural environmental SWC heterogeneity is a topic under extensive investigation<sup>19,20</sup>. Efforts to improve the use of the CRNS for exploring the spatial heterogeneity of SWC have led to research on, and development of, newer and more versatile mobile CRNSs. A mobile CRNS, whether in the form of a backpack or attached to a vehicle, behaves in precisely the same way as a stationary sensor with the same area-wide footprint. Mobility gives the CRNS technique the capacity to explore the spatial heterogeneity of soil moisture in the environment (Fig. D-2), and shows scientists and farmers where the land is dry and where it is not, which is information needed for precision irrigation. However, additional exploration into this mobile method is needed to optimize its use and availability to Member States. The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture is currently actively participating in these developments.

<sup>17</sup> Zreda, M., Shuttleworth, W. J., Zeng, X., Zweck, C., Desilets, D., Franz, T., Rosolem, R.: COSMOS: the COsmic-ray Soil Moisture Observing System, *Hydrol. Earth Syst. Sci.*, 16, 4079–4099, 2012.

<sup>18</sup> Franz, T. E., Wahbi, A., Vreughenil, M., Weltin, G., Heng, L., Oismueller, M., Strauss, P., Dercon, G., Desilets, D., Using cosmic-ray neutron sensors to monitor landscape scale soil water content in mixed land use agricultural systems, *Appl. & Environ. Soil Sci.*, Article ID 4323742, 11 pages, 2016.

<sup>19</sup> Desilets, D., Zreda, M., Ferre, T. P. A.: Nature's Neutron Probe: Land Surface Hydrology at an Elusive Scale with Cosmic-Rays, *Water Resour. Res.*, 56, W11505, 7 pages, 2010.

<sup>20</sup> Avery, W. A., Finkenbiner, C., Franz, T. E., Wang, T., Nguy-Robertson, A. L., Suyker, A., Arkebauer, T., Muñoz-Arriola, F.: Incorporation of globally available datasets into the roving cosmic-ray neutron probe method for estimating field-scale soil water content, *Hydrol. Earth Syst. Sci.*, 20, 3859 – 3872, 2016.

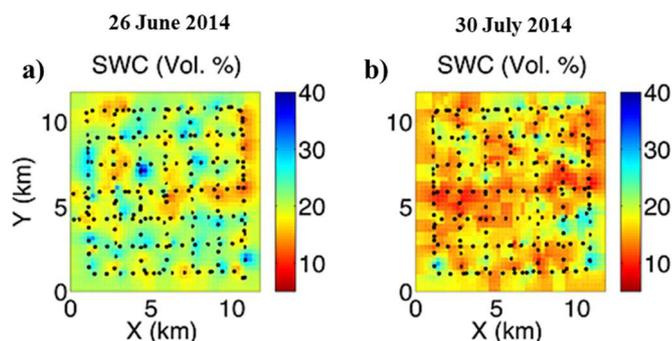


FIG. D-2. Capacity of a mobile CRNS for capturing and quantifying the spatial variability of SWC across an agricultural landscape. Black dots represent measurement locations during two survey periods with a one-month interval. (Source: Franz et al., *Combined Analysis of Soil Moisture Measurements from Roving and Fixed Cosmic-Ray Neutron Probes for Multiscale Real-Time Monitoring*, *Geophys. Res. Lett.*, 42, 3389–3396, 2015)

### D.3. Radiation Hybrid Mapping for Development of Genetic Tools to Support Livestock Breeding Programmes

140. The genetic improvement of farm animals for increased productivity of milk, meat and fibre is traditionally based on selection and breeding of high performance animals. With the recent advances in genomics, it is now possible to estimate the breeding value of animals as soon as they are born using genomic tools such as DNA chips. The development of DNA chips for animal evaluation requires sequencing and mapping of animal genomes. Genome maps pinpoint the location of specific features on the chromosomes of an organism. They are essential tools in identifying genes responsible for diseases or production and reproduction characteristics.

141. A genome map can be developed either using conventional methods or radioisotopic techniques. Conventional methods of mapping — for example, genetic linkage mapping — are based on natural recombination events and require pedigreed animals in successive generations. In the case of livestock, such methods not only involve huge costs and time (due to long generational intervals), but also result in maps with low resolution. The application of radioisotope techniques helps overcome these limitations by mimicking the genetic recombination events and speeding up the process of genome mapping for faster development of tools to increase livestock productivity.

#### D.3.1. Radioisotope techniques for mapping livestock genomes

142. Cobalt-60 or X-rays can be used to successfully irradiate and randomly break the livestock genome into several fragments. A radiation dose ranging between 30 Gy and 150 Gy is normally used and the broken chromosomal fragments of livestock genomes are recovered in rodent cells. The chromosomal ends heal quickly after irradiation and are inserted or translocated into rodent chromosomes upon fusion of cells from the livestock species with rodent cells. Around 90–100 such rodent–livestock hybrid cells are subsequently analysed for the presence or absence of DNA markers. For a given dose of radiation, markers that are located farther apart in a chromosome are more likely to be broken and placed in separate chromosomal fragments that could be integrated into different hybrid cells. The frequency of such breakage not only helps to estimate the distance between markers but also determine their order on the chromosomes, thus establishing dense maps of livestock genomes. The resolution of such radiation hybrid maps normally depends on the radiation dose used, with a higher dose increasing the map resolution. Radiation hybrid maps are thus very advantageous, particularly in producing high resolution maps of livestock genomes at relatively low costs and shorter timescales than with conventional techniques.

### D.3.2. Applications of radiation hybrid maps in livestock breeding

143. High resolution radiation hybrid maps facilitated the development of DNA chips that are widely used for breeding dairy cattle to increase milk productivity. The resultant genomic selection technology has revolutionized the artificial insemination (AI) industry by significantly increasing the annual genetic gain for milk production. The market share of young AI bulls selected based on this technology has now reached more than 50% in many industrialized countries, and other agriculture-based developing countries are looking forward to implementing the new technology in their dairy cattle production systems. Similarly, high resolution genome maps were developed for other livestock species including sheep, buffalo and pig. More recently, radiation hybrid panels developed by the Agency were used by researchers around the world to assemble the first ever draft genome sequence<sup>21</sup> and develop a high resolution whole genome map<sup>22</sup> for goats, another important livestock species for developing countries. This also helped in developing a DNA chip that could be used for breeding goats to increase meat productivity.

### D.3.3. Implications for food security and the Sustainable Development Goals

144. Radiation hybrid maps and genomic tools are not yet available for many agriculturally important livestock species, such as camel, zebu cattle, alpaca, llama, yak, donkey, mithun and rabbit. These livestock species thrive in the two main kinds of extreme environment — hot desert climates and high-altitude, cold regions — and contribute to the livelihood of large numbers of marginal farmers. For example, camels play an important role in the livelihoods of several million nomadic pastoralists in Africa and Asia and the demand for camel milk, in particular, is fast increasing in several countries.

145. Developing and implementing radiation hybrid maps and genomic tools will help establish breeding programmes for improving the productivity of such livestock and enhance food security. The demand for radiation hybrid panels from Member States to map the genome of the above-mentioned species has greatly increased in recent years. The Agency through its FAO/IAEA laboratories serves as a hub to develop and distribute such panels and other necessary resources (e.g. relevant biological reference materials, mapping resources and software tools) to its Member States.



*FIG. D-3. (Left) Irradiation of camel cells for constructing radiation hybrid panels. (Right) A. Live hybrid cells being removed from a culture dish. B. A colony of radiation hybrid cells for genome mapping. (Photos: IAEA)*

<sup>21</sup> Dong, Y., et al. (2013). Sequencing and automated whole-genome optical mapping of the genome of a domestic goat (*Capra hircus*). *Nature Biotechnology* 31, 135–141

<sup>22</sup> Du, X., et al. (2014). An update of the goat genome assembly using dense radiation hybrid maps allows detailed analysis of evolutionary rearrangements in Bovidae. *BMC Genomics* 15, 625

## **E. Human Health**

### **E.1. Advances in the Management of Prostate Cancer: Diagnosis and Therapy**

#### **E.1.1. Background**

146. Prostate cancer ranks among the three most common cancers in men worldwide and along with lung, liver, stomach and bowel cancers is among the most common causes of cancer death in males. After prostatectomy or external beam radiation therapy, 54% of patients may have biochemical recurrence, which is defined as an increased value of serum prostate-specific antigen (PSA). Local recurrence in the prostate bed after radical prostatectomy can be predicted with an accuracy of about 80%. The type of therapy used is not based on PSA levels alone but on other diagnostic imaging tests such as bone scans to exclude metastases, or computed tomography (CT) or magnetic resonance imaging to show local recurrence.

147. Despite good sensitivity in distinguishing between local recurrence and distant recurrence, available predictive tools such as nomograms do not provide information about either the real site of recurrence (e.g. lymph node vs bone, or pelvic vs extra-pelvic) or the actual number of metastases. Moreover, many patients with prostate cancer have a rising PSA that can be compatible both with local and systemic recurrences. For this reason, targeted rescue therapies cannot be planned considering the probability of risk provided by only nomograms. Patients are therefore generally directed to a salvage radiotherapy on the prostate bed (if there is suspicion of local recurrence) or to a systemic treatment with hormonal therapy such as androgen deprivation therapy if systemic recurrence is suspected.

#### **E.1.2. Diagnosis**

148. Conventional imaging, including CT, bone scintigraphy and magnetic resonance, has low accuracy values when restaging patients upon biochemical recurrence. Positron emission tomography (PET)–CT with choline showed a suboptimal sensitivity if performed in patients with early biochemical recurrence, i.e. in patients with low serum PSA after radical therapy. During the past decade, nuclear medicine techniques, such as PET with <sup>11</sup>C-choline and <sup>18</sup>F-choline, were found to be more accurate than conventional diagnostic imaging to restage patients with biochemical recurrence, allowing the differentiation between local recurrence still confined within the pelvis from systemic recurrence.

149. The optimal timing to implement rescue treatments, in order to obtain the best results from a prognostic point of view, is when the extension of the disease is small, rather than when the serum PSA levels just reach values detectable after radical therapy. In this context, the availability of a diagnostic test potentially able to differentiate between an initial relapse, or locoregional recurrence, which can be potentially curable, from a systemic recurrence only treatable through palliative approaches, may be crucial.

#### **E.1.3. Recent developments and trends**

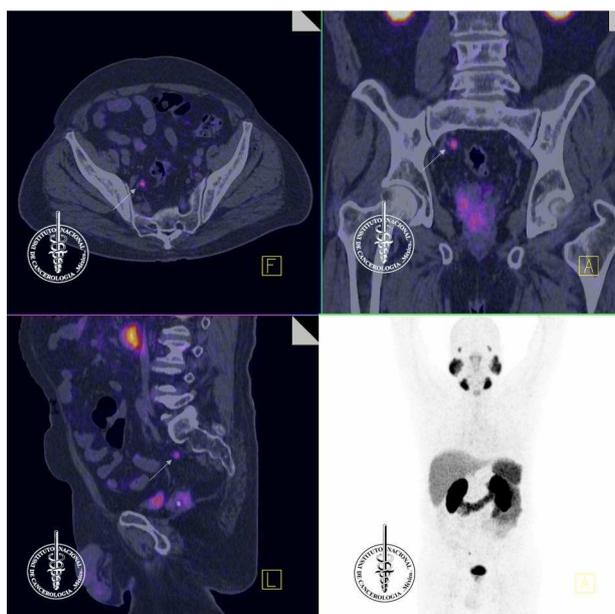
150. Recently, a new molecule that targets the prostate-specific membrane antigen (PSMA) was developed. The PSMA is a membrane enzyme that is mainly expressed in prostate cancer cells when compared with its expression in healthy prostate tissue. In preliminary studies on the diagnosis of early disease recurrence, the recently developed <sup>68</sup>Ga-PSMA, as an extracellular inhibitor of PSMA used as a radiopharmaceutical for PET–CT imaging, showed significantly higher accuracy than the

18F-choline PET–CT technique. These studies have also documented a better tumour-to-background ratio of 68Ga-PSMA PET–CT compared with 18F-choline PET–CT in identifying suspicious lesions for relapse.

151. Further studies conducted in larger patient populations with biochemical recurrence after radical therapy showed the excellent diagnostic power of 68Ga-PSMA PET–CT in restaging patients with biochemical recurrence of the disease even when serum PSA values are very low. In recent months, the use of this tracer has been the subject of particular and growing interest to the scientific community. This radiopharmaceutical has also showed high specificity (>90%) in studies using histological analysis as a reference standard for the validation of PET results (Fig. E-1). Finally, none of the studies in the literature have reported adverse events or clinically detectable pharmacological effects for this technique.

152. For the reasons explained above, the PSMA could be an excellent molecular target for the development of radiotracers for PET–CT imaging since it can detect early relapse of disease.

153. The success in the clinical performance of 68Ga-PSMA for diagnosis has led to the development of treatment with the same molecule, but labelled with a high energy isotope, such as lutetium-177 or yttrium-90. The clinical trials have shown very good results so far, but more tests are required to validate this new treatment. Using the same molecule both for diagnosis and treatment is called ‘theranostics’, which is the case for PSMA in the management of prostate cancer.



*FIG. E-1. Male patient with history of prostate cancer, treated with surgery and chemotherapy. The nuclear medicine study with  $^{68}\text{Ga}$ -PSMA PET–CT was performed to evaluate post-therapy follow-up. The arrow shows the abnormal uptake of the tracer in a lymph node, indicating the recurrence of the disease. (Photos: National Cancer Institute in Mexico.)*

## F. Water Resources

### F.1. New Developments in the Use of Isotopes in Precipitation for Diagnosing Weather and Climate

154. Precipitation is the ultimate source of all water in rivers, lakes and aquifers. The processes by which precipitation forms are fundamentally of two types: convective and stratiform. Convective precipitation, such as in thunderstorms, has a high intensity (a lot of rain over a short period of time) but occurs over a limited area (about 10–25 km<sup>2</sup>), while Stratiform precipitation has a low intensity but occurs for a much longer time and over a larger area (>500 km<sup>2</sup>). Convective precipitation, which causes more floods and other disasters, is expected to increase with a warming climate.

155. Because of differences in their atomic masses, the isotopic ratios of oxygen and hydrogen behave differently in convective or stratiform clouds and, as a result, should contain different isotope ratios. Using isotope variability to classify how much rain was of the convective or stratiform type, it is possible to gain an understanding of cloud processes and how they change in different seasons, leading to a better ability to model them both for shorter-term weather simulations and for the longer-term climate change impacts.

156. The potential use of this isotopic variability to understand how climate affects the Earth's water cycle was recognized in the early 1950s and was one of the primary considerations when the Agency established the Global Network of Isotopes in Precipitation (GNIP) in cooperation with the World Meteorological Organization (WMO) in 1960. Isotope data from GNIP led to the understanding that polar and continental ice (in the Antarctic, Arctic, Greenland, and the Andean and Himalayan mountains) contain historical records of changes in the water cycle in response to climate cooling or warming.

157. Isotope data from GNIP and other observations are known to be different in precipitation from different types of clouds, for example a quick shower versus long-lasting, slow rain. These isotope differences, however, were not thought to be sufficient to help provide a better understanding of cloud processes. Recent work at the Agency<sup>23</sup> has shown that there is, in fact, a substantial correlation between isotope ratios and cloud processes responsible for precipitation and this new knowledge is likely to greatly expand the usefulness of GNIP data for understanding both short-term weather-related, and long-term climate-related processes.

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<sup>23</sup> Aggarwal, Pradeep K., Ulrike Romatschke, Luis Araguas-Araguas, Dagnachew Belachew, Frederick J. Longstaffe, Peter Berg, Courtney Schumacher & Aaron Funk, "Proportions of convective and stratiform precipitation revealed in water isotope ratios", *Nature Geoscience*, Vol. 9, pp 624-629.

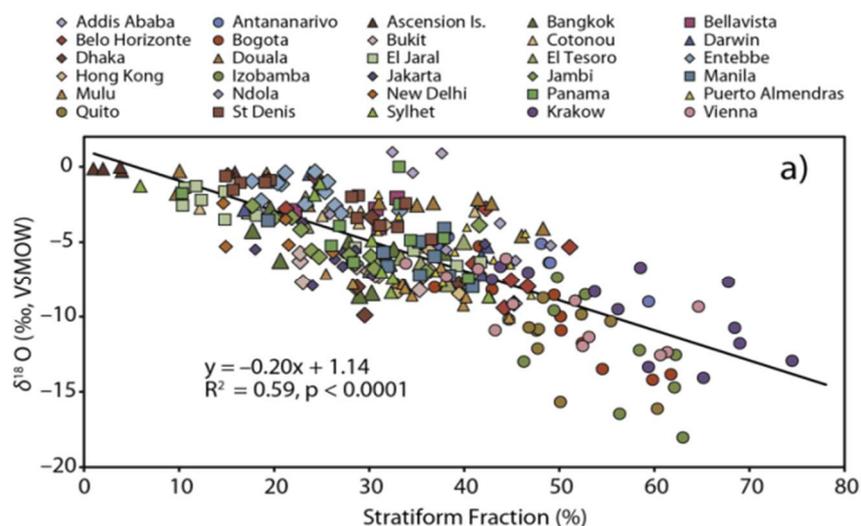


FIG. F-1. Relationship between the long-term mean oxygen-18 contents measured on composite monthly rain samples, and the fraction of stratiform precipitation in selected tropical and mid-latitude stations of the GNIP network. The remainder of the rain fraction is convective. (Source: Aggarwal, P. et al., *Proportions of convective and stratiform precipitation revealed in water isotope ratios. Nature Geoscience, Vol. 9*).

158. Data from radar on board the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched jointly by the space agencies of Japan and the USA in 1998, have been used to estimate the proportions of rain types for 1998 to 2014. When these rain type proportions are combined with isotope data from GNIP for the same time period, a robust correlation is found between the two parameters (Fig. F-1). Convective rain has higher isotope ratios and stratiform rain has lower isotope ratios. Most rain collected on a daily or monthly timescale is a mixture of the two rain types.

159. Until now, the tritium content of precipitation was thought to indicate the mixing of continental and ocean moisture. However, the recent study referred to above shows that tritium content also varies with the rain type proportions. Convective rain is found to have a higher tritium content when the clouds are very deep (reaching more than about 6 km above ground surface) and some of the ice particles grow with moisture from altitudes higher than 5 km, where tritium contents are naturally high. This is because tritium is produced in the stratosphere and reaches the troposphere (where clouds and precipitation form) by moisture exchange.

160. Routine measurements of stable isotopes and tritium in sub-daily or daily precipitation will help to better understand short-term variability in cloud dynamics responsible for changes in rain fractions. Isotope data can be used as an independent, diagnostic tool to monitor variability in, and climate change impacts on, the type of precipitation.

161. Technological developments that use precipitation partitioning based on isotope variations will help improve climate models (or global circulation models) and the simulation of convective precipitation. Accurate and improved information in this sphere can contribute to Member States' ability to predict and mitigate the impacts of climate change.

## G. Environment

### G.1. Using Isotopic Tools to Study Ocean Acidification

162. The world's oceans cover more than 70 per cent of the Earth's surface and are critical in defining its climate. If managed sustainably, the oceans also have an important role to play in providing jobs and feeding the world's population. The oceans produce more than half of the oxygen we breathe and at the same time absorb much of the excess heat and important greenhouse gases such as carbon dioxide (CO<sub>2</sub>) that we produce. Yet we now know that fundamental changes in the chemistry of seawater are occurring throughout the world's oceans.

#### G.1.1. Ocean acidification — the other CO<sub>2</sub> problem

163. Since the onset of the industrial revolution, the release of CO<sub>2</sub> has steadily increased and today the atmospheric CO<sub>2</sub> concentration has surpassed 400 ppm (0.04 per cent). Currently, the ocean is able to absorb about a quarter of the CO<sub>2</sub> that is released into the atmosphere per year. As atmospheric CO<sub>2</sub> levels steadily rise, so do CO<sub>2</sub> levels in the ocean (Fig. G-1). While at first scientists focused on the benefits of oceanic CO<sub>2</sub> removal, years of ocean observations now clearly show that there also exists a serious downside — the CO<sub>2</sub> absorbed by the ocean is changing the chemistry of seawater through a process called ocean acidification.

164. As part of this process, free hydrogen (H<sup>+</sup>) ions are released, leading to a decrease in seawater pH as well as reduced concentrations of carbonate (CO<sub>3</sub><sup>2-</sup>) ions when some of the H<sup>+</sup> ions combine with carbonate to form bicarbonate (HCO<sub>3</sub><sup>-</sup>). Palaeo reconstructions suggest that the pH of seawater has remained relatively constant for millions of years; however, in the past century and a half, since the onset of the industrial revolution, a systematic decrease in pH has been observed globally. While today's pH drop may appear relatively small (0.1 units, or an approximate 26% increase in acidity), the best currently available science-based projections<sup>24</sup> suggest that continued emissions will likely reduce surface seawater pH by another 0.4 units in this century (equivalent to an increase in acidity of approximately 150%).

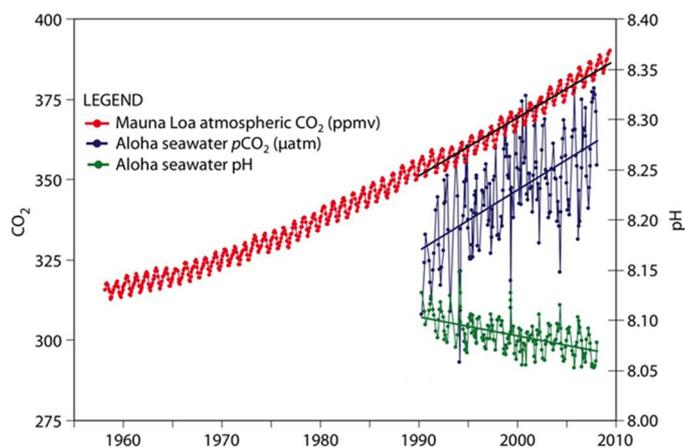


FIG. G-1. Increasing atmospheric pCO<sub>2</sub> and decreasing pH of surface ocean waters measured at the Mauna Loa Observatory, Hawaii, and the Hawaii Ocean Time-series station ALOHA. (Source: Feely R.A., Doney S.C. and Cooley S.R., 2009. Ocean acidification: Present conditions and future changes in a high-CO<sub>2</sub> world. *Oceanography* 22(4), 36–47)

<sup>24</sup> Hoegh-Guldberg, O., et al. (2007). Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science* 14 Dec 2007:Vol. 318, Issue 5857, pp. 1737-1742 DOI:10.1126/science.1152509

### G.1.2. Biological impacts of ocean acidification

165. As ocean acidification has an impact on global marine chemistry, essential biological processes are also affected, sometimes in critical ways. A wide variety of marine organisms (e.g. many molluscs, crustaceans, corals, coralline algae, and foraminifera) use carbonate ions to build their calcium carbonate skeletons. Importantly, carbonate ions are also the foundation for the calcified plates of coccolithophores, microscopic plankton that form part of the base of the marine food chain. Furthermore, dissolved CO<sub>2</sub> levels may influence the physiology of marine organisms, which often depend on a narrow range of environmental parameters including dissolved CO<sub>2</sub> and pH.

166. There are many ways in which marine organisms may be affected by sustained ocean acidification. In fish, increased oceanic CO<sub>2</sub> can have a wide variety of impacts, including altering behaviour, otolith (a fish's ear bone) formation, juvenile growth, and predator-prey behaviour. In shellfish with calcium carbonate shells, such as oysters, clams, and scallops, ocean acidification may be detrimental by impacting their growth, physiology and survival. In plankton, which other marine organisms rely on for nutrition and some of which calcify, ocean acidification can affect growth, physiology and survival with possible repercussions throughout the food web — for example, marine pteropods already have very thin shells, and these shells can dissolve rapidly in seawater with a pH of 7.8, which is the expected pH of seawater in 2100 according to current predictions. In corals, which have calcium carbonate skeletons, building and maintaining these structures under conditions of increasing ocean acidification will be more difficult, and the linkages between corals and their symbiotic dinoflagellates can also be compromised, leading to coral bleaching. Widespread observations suggest that elevated CO<sub>2</sub> has a strong bleaching effect on corals (Fig. G-2).



FIG. G-2. Widespread coral bleaching, Marshall Islands. (Photo: IAEA)

### G.1.3. The application of nuclear techniques to understanding the impacts of ocean acidification

167. Several radioisotopes are uniquely suited to quantifying the biological effects of ocean acidification, including calcium-45 to study calcification rates, carbon-14 to assess primary production of marine phytoplankton, strontium-85 to assess biomineralization rates, zinc-65 to study the metabolic rates of marine organisms, and a suite of radiolabelled trace elements (e.g. silver-110m, cadmium-109, cobalt-57, cobalt-60, manganese-54, selenium-75) to study pH dependent rates of bioaccumulation and depuration. The isotopic composition of boron-10 and boron-11 in long-lived corals can be used to reconstruct seawater pH in order to understand past environmental conditions and put in context the predicted changes to future ocean pH.

168. Tremendous advances in ocean acidification science<sup>25</sup> have been made in recent years. Today's experiments are strengthened using radioisotopes with a multi-tracer approach to investigate how projected decreases in ocean pH will affect marine organisms. At the Agency's Environment

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<sup>25</sup> The Ocean Acidification International Coordination Centre serves as a hub for information in this sphere <https://www.iaea.org/ocean-acidification/page.php?page=2181>

Laboratories, controlled experiments on the effects of ocean acidification on select corals, shellfish and fish show pronounced metabolic and physiological changes after prolonged exposure to reduced environmental pH. Advances in the application of radioisotopes, including paired isotopic studies (e.g.  $^{134}\text{C}$ ,  $^{137}\text{C}$ ) are enabling new insights into the wide-ranging impacts of ocean acidification with added cumulative stressors, such as temperature and/or dissolved oxygen, in future oceanic environments.

## H. Radiation Technologies

### H.1. Cultural Heritage: Exploration and Preservation Using Radiation Technologies

169. Cultural heritage objects are often invaluable and cherished artefacts that require careful handling and sophisticated preservation techniques. Radiation techniques are harnessed to provide detailed examinations of objects, strengthen them, and help control their deterioration or degradation. Artefacts can also be disinfested, if necessary, and thus better preserved. Radiation techniques are becoming more advanced and increasingly acceptable to concerned institutions responsible for managing cultural artefacts.

#### H.1.1. Exploration and examination

170. Radiation techniques can help to investigate the authenticity of a painting or establish whether there is another layer below the surface, ascertain whether an artefact is made of gold or just coated with gold, or assess the delicacy of an old statue before it is transported — all without any damage to the object. X-ray fluorescence (XRF) is a tool that can aid in elemental analysis of materials and is frequently used in museums to study a variety of artefacts (Fig. H-1).

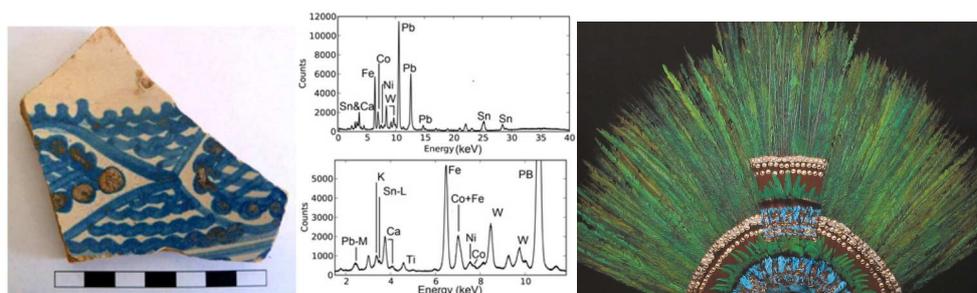


FIG. H-1. Elemental analysis of a piece of pottery from the seventh century (left) and a rare sixteenth-century Mexican head piece which was analysed using a handheld XRF device to reveal the original gold embellishment and later added features (right). (Photo: IAEA)

171. Just as medical radiography images the internal parts of a human body, so radiographic techniques can reveal the internal structure of statues and pinpoint possible weaknesses. A variety of radiographic techniques (such as conventional X-ray radiography, gamma radiography, accelerator-based radiography, radioscopy, beta radiography or secondary electron radiography, electron emission radiography, neutron radiography, autoradiography and computer-assisted tomography) aid in the examination and exploration of works of art (Figs H-2, H-3 and H-4).



FIG. H-2. Variations of X-ray techniques such as particle-induced X-ray emission and accelerator-based techniques are routinely used in museums to study art objects such as this example from Museo Civico d'Arte Antica, Turin, Italy. (Photo: INFN, Italy)



FIG. H-3. The radiograph suggests that the head and the trunk of this statue of Jupiter, located in Vieil-Évreux, France, were joined by welding. (Photo: J.L. Boutaine)

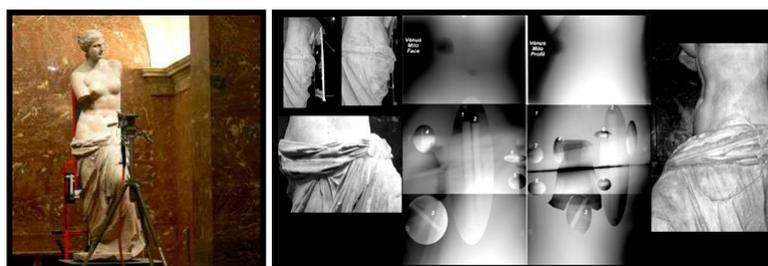


FIG. H-4. Gamma radiograph showing the internal structure of the Venus de Milo statue in the Louvre Museum, France, used for decision-making before transporting. (Photos: IAEA)

### H.1.2. Use of radiation based techniques for preservation and consolidation of artefacts

172. Infection of cultural heritage artefacts can lead to accelerated deterioration and pose a health risk to those handling the object. Conventional disinfection techniques used in medicine and agriculture to treat large quantities of objects, such as fumigation, employ toxic chemicals like formaldehyde, ethanol or ethylene oxide, or require severe conditions such as high temperature and pressure that many cultural artefacts could not tolerate. Experiments in the 1950s (gamma irradiation of xylophagous insects) first indicated the biocide effect of ionizing radiation. As radiation processing technology has matured in industry, its use in the disinfestation of cultural heritage artefacts has grown. Radiation treatment, which is well established for the sterilization of medical products, food and tissue grafts, offers an additive-free, room temperature option for the treatment of cultural heritage objects. As radiation not only obviates the use of toxic chemicals, but also ensures uniform, thorough penetration irrespective of the size and shape of the object and does not leave behind any residual harmful substances, it is an attractive option for cultural heritage preservation — safe for personnel as well as the environment. Radiation decontamination is performed safely by authorized persons in approved facilities.

#### Disinfection of the Ramses II mummy

173. The Ramses II mummy, displayed at the Egyptian Museum in Cairo, was transferred to France for an exhibition in 1976 and was found to be infested with larvae, insects and a large variety of fungi, though without any pathogenic bacteria. The French National Museum of Natural History, in

agreement with the Egyptian authorities, disinfested the mummy in 1977 by using gamma irradiation at the Nucléart Regional Conservation Workshop. A consortium of laboratories and museums in Paris and Grenoble managed the radiation treatment after careful planning and testing. In order to determine the irradiation dose to effectively eradicate all the fungi (more than sixty species) without affecting the other components such as the hair, textiles, skin and teeth of the mummy, over four hundred samples from other mummies were taken for testing. The large (1.72 metre long) uneven form of the mummy, as well as the presence of multiple materials inside, necessitated complex dosimetry calculations using precise mathematical models to impart a uniform dose of 18 kGy. The Ramses II mummy was irradiated successfully after validation using two model mummies and sent back to Egypt where it remains in good condition forty years later.

### **Project RADIART, Portugal**

174. Eighteenth-century Portuguese tiles at the National Tile Museum, Lisbon, were treated with a radiation dose of ~4 kGy to deactivate both the bacteria at the surface and fungi inside, which were responsible for green staining. The irradiation process showed a microbial efficiency higher than 70%.

### **Casaccia Research Centre, Italy**

175. The studies carried out at the Casaccia Research Centre of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development on the effects of gamma radiation on materials showed that ionizing radiation is extremely efficient in disinfestations against harmful insects (at doses of 0.2–0.5 kGy) and microfungi (at doses of 3–8 kGy). The studies showed that even with a radiation dose of 10 kGy, the colour fastness of photographic prints on pure cellulose or paper was preserved irrespective of whether the process involved the use of albumen, silver gelatin, collodion or aniline, signalling the usefulness of radiation technology to treat old and microbially infested photographs.

### **Time capsule, Brazil**

176. A box made of wood and lead containing some of the oldest documents from the time of the Empire of Brazil (nineteenth century) was found inside a cornerstone in the city of Rio de Janeiro. The box was treated with a radiation dose of 8–10 kGy at the Multipurpose Gamma Irradiation Facility at IPEN-CNEN, the Nuclear and Energy Research Institute, Brazil, before restoration (Fig. H-5).



*FIG. H-5. The time capsule undergoing fungi treatment. (Photo: P. Vasquez, Nuclear and Energy Research Institute IPEN/CNEN, São Paulo, Brazil)*

### **Khroma — preserving a frozen baby mammoth**

177. In 2008, in Siberia, Russian Federation, a frozen specimen of a baby mammoth was recovered. Named Khroma, after the river on the edges of which it was found, this baby mammoth, estimated to be over 50 000 years old, is perhaps the oldest specimen known. Although well preserved, any traces of bacteria or other potentially pathogenic organisms it could carry needed to be inactivated. Gamma irradiation emerged as the most appropriate technique for a non-destructive biocidal treatment of the entire specimen. In July 2010, the frozen baby mammoth was subjected to a dose of 20 kGy in Grenoble, France, and is now well preserved and on display to the public. (Fig. H-6).



*FIG. H-6. Baby mammoth 'Khroma' preserved after irradiation in July 2010.  
(Photo: Dr. Quoc Khoi TRAN, ARC-Nucléart, CEA-Grenoble)*



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