NUCLEAR TECHNOLOGY REVIEW

2015

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EXECUTIVE SUMMARY

With 438 reactors operating at the end of 2014, nuclear energy had a global generating capacity of 376.2 GW(e). There was only one permanent shutdown. There were five new grid connections and three construction starts on new reactors. Near and long term growth prospects remained centred in Asia, particularly in China. Of the 70 reactors under construction, 46 were in Asia, as were 32 of the last 40 reactors that have been connected to the grid since 2004.

Thirty countries currently use nuclear power and about the same number are considering, planning or actively working to include it as part of their energy mix. Of the 30 operating countries, 13 are either constructing new plants or actively completing previously suspended construction projects, and 12 are planning either to construct new plants or to complete suspended construction projects. Several countries that have decided to introduce nuclear power are at advanced stages of infrastructure preparation.

The IAEA's 2014 projections show a growth between 8% and 88% in nuclear power capacity by the year 2030. Growth of population and demand for electricity in the developing world, recognition of the role nuclear power plays in reducing greenhouse gas emissions, the importance of security of energy supply and the volatility of fossil fuel prices point to nuclear energy playing an important role in the energy mix in the long run.

Safety improvements have continued to be made at nuclear power plants (NPPs) throughout the world. These have included identifying and applying lessons learned from the accident at the Fukushima Daiichi Nuclear Power Plant, improving the effectiveness of defence in depth, strengthening emergency preparedness and response capabilities, enhancing capacity building, and protecting people and the environment from ionizing radiation.

Although considerable exploration and development expenditures have been reported, many new mining projects have been or are expected to be delayed owing to low uranium prices. Unconventional uranium resources to further expand the resource base and research into economic recovery of uranium from the oceans gave encouraging results.

Global enrichment capacity remained above the total annual demand, with other fuel cycle activities operating at relatively constant levels. To contribute to the assurance of supply framework, significant work has been done on the financial, legal and technical arrangements for establishing the IAEA low enriched uranium (LEU) bank in Kazakhstan.

Practically all Member States have to manage some form of radioactive waste. The Scientific Forum, held during the 58th regular session of the IAEA's General Conference, emphasized the need for a comprehensive, integrated, cradle-to-grave approach for radioactive waste management, and highlighted the fact that solutions are available for implementation.

Due to deferred policy decision on spent fuel management in many Member States, the global amount of spent fuel in storage continued to increase. About 10 000 t of heavy metal (HM) were discharged as spent fuel from all NPPs in 2014, bringing the cumulative amount to approximately 380 500 t HM, of which about 258 700 t HM were stored in either at reactor or away-from-reactor facilities.

Significant decommissioning experience gained since the turn of the century will help tackle the considerable work expected in this field in the years to come: 149 nuclear power reactors worldwide have been permanently shut down or are undergoing decommissioning, including 17 that have been fully decommissioned. Slightly more than half of all the operating reactors are more than 30 years old and about 14% of them are more than 40 years old. Although some may continue to operate for up to 60 years, many will be retired from service within the next two decades. In addition, more than 480 research reactors and critical assemblies, and several hundred other nuclear facilities, such as radioactive waste management or fuel cycle facilities, have been decommissioned or are undergoing decommissioning.

Similarly, some countries have built up appropriate technical resources and expertise in remediating land affected by past practices and accidents, but many national programmes still face significant challenges impeding the implementation of remediation programmes. Japan has achieved significant progress in remediating land affected by the Fukushima Daiichi accident and there was good coordination between remediation activities on the one hand and reconstruction and revitalization efforts on the other. Sharing the lessons learned from the remediation works with the international community is of paramount importance.

The international nuclear data community has embarked on the task of unifying Evaluated Nuclear Data Files, the backbone of all nuclear technology, through the Collaborative International Evaluated Library Organization (CIELO) project of the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA). This project will create single files for the highest priority nuclei, namely hydrogen, oxygen, iron and the major actinides, that can be used by all evaluation projects for all applications.

Two large scale accelerator projects, both in Europe, were launched in 2014. The IAEA’s new multitechnique experimental facility, set up as an end station of the X ray fluorescence beamline at the Elettra facility in Trieste, Italy, will enable access to a state of the art synchrotron facility for research groups from Member States, especially developing ones.

The majority of the 247 research reactors and critical facilities in operation remain heavily underutilized and are on average over 45 years old. Six countries are constructing new ones, while several others are planning or considering building new ones. Initiatives such as the Internet Reactor Laboratory and the IAEA Designated International Centre based on Research Reactor are aimed at fostering international cooperation in education and training and the efficient use of such facilities.

While there were no major supply shortages of the medical isotope molybdenum-99 during 2014, operational challenges at processing facilities and older research reactors continue.

Global activities to minimize the use of high enriched uranium (HEU) in the civilian nuclear sector continued, with 92 of 200 research reactors within the scope of implementation of the USA's Global Threat Reduction Initiative (GTRI) having now been converted LEU fuel or confirmed as shut down. By the end of 2014, the take-back programmes for HEU fuel of USA and Russian origin were 76% and 86% complete, respectively.

The IAEA's Nuclear Sciences and Applications Laboratories at Seibersdorf, near Vienna, have assisted Member States in enhancing their access to the peaceful uses of nuclear technologies since 1962. Much of this assistance is provided via the IAEA technical cooperation programme, responding directly to the needs of Member States in areas such as food and agriculture, human health, the terrestrial environment and nuclear instrumentation. The IAEA's new initiative, the Renovation of the Nuclear Application Laboratories (ReNuAL) project, is the first comprehensive renovation of the laboratories since their establishment. It is aimed at upgrading them to fit for purpose laboratories to help Member States meet global development challenges over the next two decades.

Nuclear and nuclear related technologies are playing an important role in animal health, particularly in relation to disease diagnosis and the characterization of pathogenic organisms.

Vaccines are important tools to protect animals and humans from disease. Recent developments in vaccine irradiation allow for the creation of vaccines that are metabolically active yet non-replicating and therefore produce an immune system response similar to exposure to a live pathogen.

Early, rapid diagnosis is critical for controlling the spread of transboundary diseases. Although enzymes and fluorescent dyes are effective for diagnosis and practical for use in the field, nuclear techniques are needed in cases where high levels of sensitivity and specificity are needed (e.g. to diagnose H5N1 avian influenza, foot-and-mouth disease, Rift Valley fever or African swine fever).

A dramatic improvement in the diagnosis of infectious diseases occurred with the advent of nucleic acid amplification platform technologies (e.g. polymerase chain reaction). The main advantage of these techniques is that extremely low levels of infection can be detected in animals allowing for the detection of a pathogen before the onset of disease. Early detection of pathogens is essential for the prevention of an outbreak of disease such as the Ebola virus disease (EVD) outbreak in West Africa in 2014. The IAEA complemented international efforts by helping African Member States to develop or strengthen national and regional capacities and networking in the application of quick and accurate diagnostic and control technologies. One such technological platform, the Reverse Transcriptase Polymerase Chain Reaction (RT-PCR), is recognized as a fast and efficient EVD diagnostic technique.

The stable isotope analysis (SIA) technique can be used to provide the means to understand the epidemiology of zoonotic diseases. Using stable isotopes to characterize a population involves examining the isotopic signatures of a few individuals that are representative of the entire population. Once the isotope profile of a particular population is known, any individuals from the population can provide information on the global migration of that species.

Effectively measuring the dose of radiation to which a patient is exposed to during radiation therapy and diagnosis is important either to verify that the treatment is carried out as prescribed or to estimate the risk associated with a patient being exposed to radiation during a medical imaging procedure.

Diagnostic X ray imaging is used in a diverse range of examination types, from simple projection radiography to advanced cross-sectional dynamic imaging. This has resulted in the development of a wide range of dosimetric quantities, measuring instruments and techniques, all of which present challenges to those working in the clinical environment.

A key requirement in the radiotherapy process is that there should be consistent reference dosimetry standards and procedures. New standards and guidelines are now being developed to keep pace with advances in radiotherapy techniques and technology.

There has been a recent increase in radiotherapy techniques that use small fields, which has increased the uncertainty of clinical dosimetry and called into question the appropriateness of applying existing reference dosimetry protocols which were developed for larger fields. A code of practice for dosimetry is being developed that will standardize the dosimetry of small fields.

Calibrated, well-type chambers are the preferred dosimeter for the calibration of radioactive sources used in brachytherapy. However, there is a lack of internationally harmonized quality assurance/quality control guidelines for all sources used in brachytherapy and also for the associated recommended dosimetry instrumentation. Efforts are being made to establish absorbed dose to water standards in order to achieve harmonization with external beam radiotherapy dosimetry codes of practice.

Impressive progress has been made in the development of radioisotope production technologies which has allowed broader access to a number of new radionuclides, including gallium-68, copper-64, zirconium-89 and zinc-63, and facilitated the development of accelerator based technologies for the commercial production of technetium-99m, which still remains the most widely used diagnostic radionuclide. The availability of new radioisotopes for medical applications may solve as yet unforeseen clinical problems. These advancements are dramatically changing the nuclear medicine landscape.

Securing access to safe drinking water, as well as adequate fresh water supply for sanitation, food production and energy generation is a continuing challenge for many countries. New isotope tools and approaches, coupled with innovative analytical developments, have contributed in recent years to the substantial expansion in the use of environmental isotopes to understand, monitor and assess the impact of climate change on water and other natural resources.

Comprehensive, science based water resources assessments are critical for sustainable development. Simpler, cheaper and low maintenance laser based instruments are contributing to the expansion of applications based on stable isotopes. The demand for newer isotope tools for dating groundwater, requiring more sophisticated analytical methods to measure isotopes of noble gases and long lived radionuclides, is expected to continue in the near future.

Increases in atmospheric carbon dioxide (CO_2) are progressively affecting the marine environment. Radionuclides offer powerful tools to understand the changing carbon cycle and how it affects organisms. They can also be used to reconstruct palaeo-changes of seawater chemistry in order to understand present changes and how these may affect oceans in the future.

When CO_2 is absorbed by the ocean, it acidifies the water, which in turn affects marine organisms. Radioisotopes are used to investigate changes to processes in marine organisms such as calcification, biomineralization and metabolism in response to this increasing acidity.

Nuclear and stable isotope techniques are used to reconstruct past pollution events, track pollution trends and evaluate the effectiveness of pollution control measures. They are also used to study land based pollution sources of nutrients which cause coastal eutrophication, to distinguish between anthropogenic and natural concentrations of pollutants, to identify pollution sources for forensic pollution studies and to identify biotoxins related to harmful algal blooms.

Oil pollution of coastal waters is a worldwide environmental problem caused by petroleum hydrocarbon discharges. There is an increasing need for sensitive and reliable methods to monitor oil pollution and its impact, and to develop methods that identify the origin of oil pollution for regulatory purposes. The analysis of stable carbon isotope ratios in petroleum hydrocarbons is used in combination with chemical methods to fine tune the fingerprinting of oil slicks with the aim of tracing oil sources in the marine environment.

A. POWER APPLICATIONS

A.1. Nuclear Power Today

As of 31 December 2014, there were 438 operational nuclear power reactors worldwide, with a total capacity of 376.2 GW(e)[1] (see Table A.1 [A.1]). This represents a slight increase of some 4.5 GW(e) in total capacity, as compared to 2013.

Of the operational reactors, approximately 81.5% are light water moderated and cooled, 11.2% are heavy water moderated and cooled, 3.4% are light water cooled and graphite moderated, and 3.4% are gas cooled reactors (Fig. A.1). Two are liquid metal cooled fast reactors.

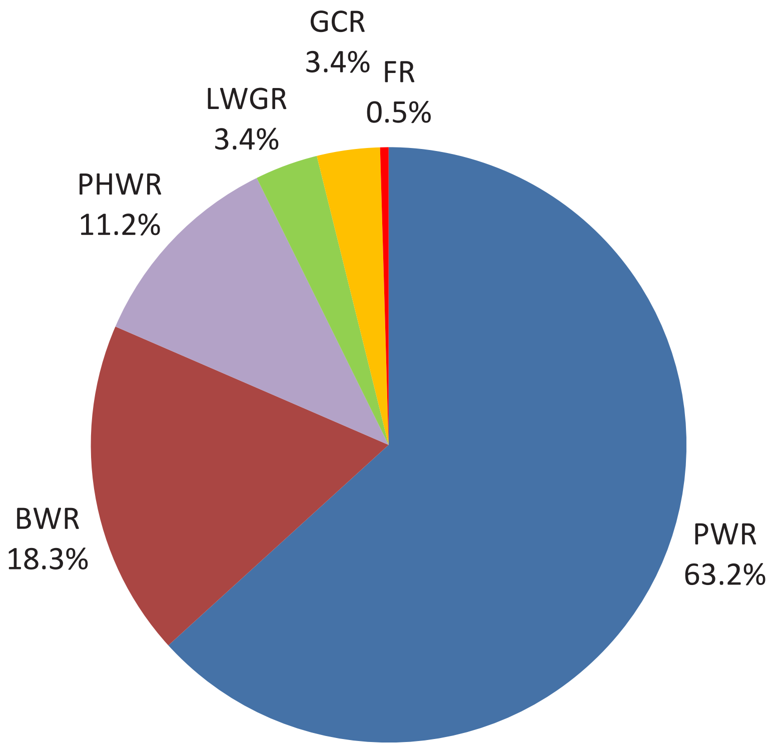


FIG. A.1. Current distribution of reactor types. (BWR: boiling water reactor; FR: fast reactor; GCR: gas cooled reactor; LWGR: light water cooled, graphite moderated reactor; PHWR: pressurized heavy water reactor; PWR: pressurized water reactor) [A.1].

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

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2014)[a]

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2014		Total operating experience through 2014	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Argentina	3	1 627	1	25	5.3	4.1	73	2
Armenia	1	375			2.3	30.7	40	8
Belarus			2	2 218				
Belgium	7	5 927			32.1	47.5	268	7
Brazil	2	1 884	1	1 245	14.5	2.9	47	3
Bulgaria	2	1 926			15.0	31.8	157	3
Canada	19	13 500			98.6	16.8	674	6
China	23	19 007	26	25 756	123.8	2.4	181	7

For footnotes see p. 11

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2014)[a] (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2014		Total operating experience through 2014	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Czech Republic	6	3 904			28.6	35.8	140	10
Finland	4	2 752	1	1 600	22.6	34.7	143	4
France	58	63 130	1	1 630	418.0	76.9	1 990	4
Germany	9	12 074			91.8	15.8	808	1
Hungary	4	1 889			14.8	53.6	118	2
India	21	5 308	6	3 907	33.2	3.5	418	6
Iran, Islamic Republic of	1	915			3.7	1.5	3	4
Japan	48	42 388	2	2 650	0.0	0.0	1 694	4
Korea, Republic of	23	20 717	5	6 370	149.2	30.4	450	1

For footnotes see p. 11

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2014)[a] (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2014		Total operating experience through 2014	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Mexico	2	1 330			9.3	5.6	45	11
Netherlands	1	482			3.9	4.0	70	0
Pakistan	3	690	2	630	4.6	4.3	61	8
Romania	2	1 300			10.8	18.5	25	11
Russian Federation	34	24 654	9	7 371	169.1	18.6	1 157	3
Slovakia	4	1 814	2	880	14.4	56.8	152	7
Slovenia	1	688			6.1	37.3	33	3
South Africa	2	1 860			14.8	6.2	60	3
Spain	7	7 121			54.9	20.4	308	1

For footnotes see p. 11

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2014)[a] (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2014		Total operating experience through 2014	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Sweden	10	9 470			62.3	41.5	422	6
Switzerland	5	3 333			26.5	37.9	199	11
Ukraine	15	13 107	2	1 900	83.1	49.4	443	6
United Arab Emirates			3	4 035				
United Kingdom	16	9 373			57.9	17.2	1 543	7
United States of America	99	98 639	5	5 633	798.6	19.5	4 012	4
Total[b, c]	438	376 216	70	68 450	2 410.4		16 096	10

[a] Data are from the IAEA’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, 5032 MW(e) in operation; 2 units, 2600 MW(e) under construction; 40.8 TW·h of nuclear electricity generation, representing 18.9% 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 (200 years, 1 month).

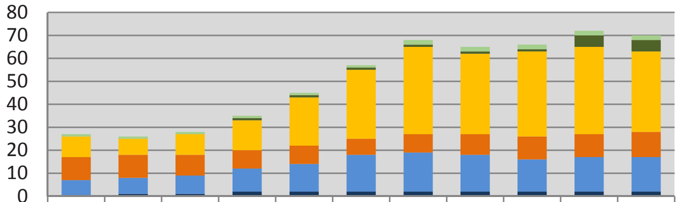
In Japan, all 48 operational reactor units were kept off-line in 2014. In November 2014, the governor of Kagoshima Prefecture approved the restart of Sendai-1 and -2, which became the first units in the country to be cleared by the nuclear regulatory authority in accordance with the new safety standards imposed after the March 2011 Fukushima Daiichi accident. In December 2014, the Nuclear Regulation Authority in Japan approved the restart of Takahama 3 and 4 reactor units.

In 2014, five new reactors were connected to the grid: Atucha-2 (692 MW(e)) in Argentina, Ningde-2 (1018 MW(e)), Fuqing-1 (1000 MW(e)) and Fangjiashan-1 (1000 MW(e)) in China and Rostov-3 (1011 MW(e)) in the Russian Federation. Construction of the Atucha-2 reactor unit had originally started in 1981 but it was delayed and reactivated only in 2009.

There was only one permanent shutdown in 2014. The single unit Vermont Yankee, USA, ended commercial operations on 29 December 2014 owing to financial considerations.

There were only three construction starts in 2014: Belarusian-2 in Belarus, Barakah-3 in the United Arab Emirates and CAREM-25, a small integral type of pressurized light water reactor (LWR) design in Argentina.

As of 31 December 2014, 70 reactors were under construction. As in previous years, expansion, as well as near and long term growth prospects, remain centred in Asia (Fig. A.2), particularly in China. Of the total number of reactors under construction, 46 are in Asia, as are 32 of the last 40 new reactors to have been connected to the grid since 2004.



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

FIG. A.2. Number of reactors under construction by region [A.1].

In 2014, several countries made significant progress towards their first NPP. In the United Arab Emirates, the Federal Authority for Nuclear Regulation approved the application of the Emirates Nuclear Energy Corporation to build two more units on the Barakah site. Barakah Units 1, 2 and 3 are already under construction and expected to be operational by 2017, 2018 and 2020, respectively.

Belarus poured the first concrete of its second unit in April 2014 and has moved to the above ground stage of construction on Unit 1. The two units are WWER-1200 reactors to be constructed under a contract signed with the Russian Federation's Atomstroyexport in July 2012.

Turkey continues to develop its nuclear power programme infrastructure. In December 2014, the Ministry of Environment and Urban Planning approved the environmental impact assessment of the four proposed WWER-1200 units at Akkuyu. The Turkish regulatory body enlisted in October 2014 a technical support organization to assist with its review and assessment of the construction licence application for Akkuyu, expected to be submitted in 2015. Following an intergovernmental agreement signed with Japan in 2013, Turkey is also working on a second NPP project at Sinop and has started, in cooperation with its partners, site investigations and the preparation of a technical feasibility study.

In January, Poland's Council of Ministers confirmed the decision to introduce around 6000 MW(e) nuclear capacity into the energy mix, with plans to have the first unit operational by 2024.

In 2013, Viet Nam completed feasibility studies of two sites for NPPs in Ninh Thuan with a total capacity of 4000 MW(e). Viet Nam hosted a follow-up Integrated Nuclear Infrastructure Review (INIR) mission in November 2014 that provided feedback on the progress of actions made in the development of its nuclear infrastructure. Kenya, Morocco and Nigeria officially requested INIR missions to be scheduled in 2015.

Several countries that have decided to introduce nuclear power are at advanced stages of infrastructure preparation. Following a 2011 intergovernmental agreement with the Russian Federation on cooperation for the construction of the two unit Rooppur NPP, Bangladesh started site preparatory work in 2013, and construction is expected to begin in 2016. In October 2013, Jordan selected the Russian Federation's Atomstroyexport as a preferred vendor, and is currently working on the characterization of the Amra site. An INIR mission in August 2014 concluded that Jordan had made progress in developing its nuclear infrastructure and made recommendations for further actions.

Several countries continue to consider introducing nuclear power. Some are actively preparing to make an informed decision on the potential implementation of a nuclear power programme and several countries are developing their energy strategies to include a nuclear power option. At this stage, the focus is on developing the comprehensive legal and regulatory infrastructure necessary to support a nuclear power programme in addition to developing the required human resources.

Capacity building continues to be important in ensuring the continued availability of competent personnel for the safe, secure and sustainable management or phasing out of a nuclear power programme. The importance of capacity building was also underlined in the IAEA Action Plan on Nuclear Safety (approved by the General Conference in 2011), which calls upon Member States with nuclear power programmes, as well as those planning to embark on such a programme, to strengthen, develop, maintain and implement their capacity building programmes. Attending the IAEA's International Conference on Human Resource Development for Nuclear Power Programmes: Building and Sustaining Capacity, held in Vienna in May 2014, over 300 participants from 65 Member States and 5 international organizations discussed the global challenges of capacity building and highlighted the importance of ensuring a sustainable supply of qualified human resources.

Counterfeit, fraudulent and suspect items (CFSIs) are becoming an increasing concern for operating organizations and regulators, and instances of CFSIs and related quality documentation are being detected. In some cases, NPPs that are operating or that are under construction have experienced significant economic impacts, including temporary plant shutdowns, as consequences of using CFSIs. Operating organizations are taking a growing number of preventive measures, including increased awareness and training, better procurement specifications and inspections as well as a reduced use of brokers. Reporting on CFSIs, including those detected prior to plant installation, is increasingly required by regulators. To help address this issue, the IAEA held a technical meeting in September 2014 focused on procurement activities and CFSIs. It has also started developing technical guidelines on procurement engineering. These include recommendations on how to avoid the use of CFSIs.

Of the 438 operational nuclear power reactors, 225 have been in service for 30 years or more (see Fig. A.3). There are plant life management models for long term operation beyond licence periods. A model followed in the USA and in some other Member States is based on the Licence Renewal Application concept. In this model, the licensing authority issues an operating licence for up to 40 years and it can be renewed for an additional period of a maximum of 20 years for each renewal application. A total of 73 of the 99 reactors operating in the USA have received 20 year licensing renewals as of the end of 2014. Another licensing model is based on the Periodic Safety Review (PSR) process, primarily used for reactors in Europe. Under this model, the licensee should carry out PSR process at regular intervals, typically every ten years, to confirm the licensing terms

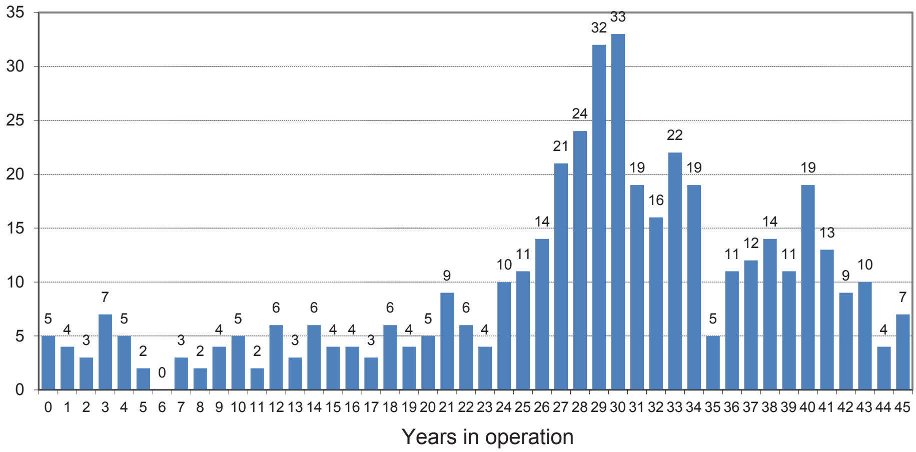


FIG. A.3. Distribution of operational power reactors by age as of 31 December 2014 [A.1].

and environmental conditions. PSR is a comprehensive review of all important aspects of safety, aimed at identifying and addressing gaps based on current licensing requirements. One of the main challenges for long term operation is to develop and implement ageing management programmes to assess the integrity of essential structures, systems and the remaining lifetime of critical components. The IAEA has developed a programmatic guide and many component specific guides for ageing management.

The Doel-3 and Tihange-2 units in Belgium were shut down in 2012 after flaws were discovered in their reactor pressure vessels (RPVs). After thorough investigations and after the regulatory requirements had been met, they were restarted in May 2013. However, further metallurgical testing led the utility, Electrabel, to shut them down in March 2014 until uncertainties regarding the effect of neutrons on the mechanical strength of the RPV steel were resolved. To share lessons learned on the structural integrity, an IAEA training course in September 2014, hosted by the Research Centre for Energy, Environment and Technology (CIEMAT) in Madrid, Spain, focused on the assessment of the degradation mechanisms of primary components in NPPs.

Reassessments of safety as a result of the Fukushima Daiichi accident have, in many cases, resulted in additional capital expenditure to meet new regulatory requirements. This will have an impact on the cost of nuclear power generation and may have an impact on the economic sustainability of long term operation. The IAEA is preparing a new technical guide on approaches to economic assessment for the long term operation of NPPs.

A.2. The Projected Growth of Nuclear Power

In the IAEA's 2014 projections [A.2], nuclear power capacity grows from a current 372 GW(e) to 401 GW(e) in the low projection and to 699 GW(e) in the high projection by 2030. These projections reflect a positive growth of 8% and 88% for the low and high projections, respectively. The 2014 projections are lower by about 23 GW(e) in the high case and by 34 GW(e) in the low case[2] as compared to the 2013 projections. Factors contributing to this decline include earlier than anticipated reactor retirements, delayed new builds as well as added costs attributable to the implementation of additional safety related modifications. Nevertheless, interest in nuclear power remains strong in some regions, particularly in countries with developing economies and energy needs. The continued growth suggests that the fundamentals supporting continued use of nuclear power have not changed.

These projections 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 in IAEA Member States. The projections are prepared by assessing the plausibility of each project in the light of the general assumptions for the low and the high cases. 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.

Over the short term, the low price of natural gas and increasing capacities of subsidized renewable energy sources are expected to affect nuclear growth prospects in some regions of the developed world. These low natural gas prices are partly due to low demand as a result of macroeconomic conditions, as well as technological advances. Moreover, the ongoing financial crisis continues to present challenges for capital intensive projects such as nuclear power. The assumption adopted by the experts was that the above mentioned challenges, in addition to the Fukushima Daiichi accident, may temporarily delay deployment of some NPPs. The underlying fundamentals of growth in population and demand for electricity in the developing world, recognition of the role that nuclear energy plays in avoiding CO_2 emissions, issues regarding security of energy supply and price volatility of fossil fuels suggest that nuclear energy will continue to play an important role in the energy mix over the longer term.

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[2] The projections consist of both available capacity (currently supplying electricity to the grid) and installed nominal capacity (available, but not currently supplying electricity to the grid).

CO_2 emissions already avoided by nuclear power

Nuclear power has been part of the world's electricity supply for over 50 years. As an added benefit, nuclear energy avoids CO_2 emissions. Figure A.4 [A.3] shows the historical trends of CO_2 emissions from the global electricity sector and emissions avoided by using hydropower, nuclear energy and other renewable energy sources. The power sector at the bottom of the chart shows the actual CO_2 emissions produced over the past 40 years. The incremental values shown above the actuals represent the emissions avoided by nuclear, hydro, and renewables, amounting to nearly 6 gigatonnes (Gt) in 2011, or a saving in CO_2 emissions of one third relative to what the total would otherwise have been. It is estimated that just over a third of these CO_2 emission savings (2.1 Gt) came from nuclear power.

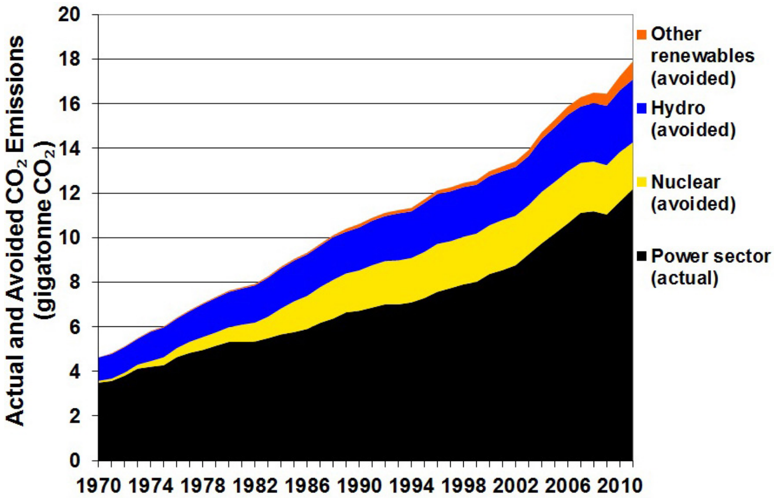

FIG. A.4. Global CO_2 emissions from the electricity sector and emissions avoided by using three low-carbon generation technologies. (Data source: Ref. [A.3].)

Such estimates of avoided emissions depend on assumptions on what replacement electricity would have been used. For the avoidance estimates, it was assumed that the electricity generated would have been produced by increasing generation using coal, oil and natural gas in proportion to their respective shares in the electricity mix. This is a conservative approach since it is more likely that coal would have been substituted for nuclear energy due to its domestic abundance.

More information on nuclear power and climate change is available in Ref. [A.4].

The International Energy Agency of the Organisation for Economic Co-operation and Development (OECD/IEA) also publishes projections of the global growth in nuclear power. According to the OECD/IEA's World Energy Outlook 2014 [A.5], under its central scenario, referred to as the New Policies Scenario, global nuclear generating capacity will reach 543 GW(e) in 2030. This is essentially unchanged from a year ago and is nearly the average of the IAEA's projections. Figure A.5 compares the IAEA's 2014 projections [A.2], the OECD/IEA's 2014 scenarios[3], and the Word Nuclear Association's (WNA) 2013 projections [A.6]. The high scenarios from the three organizations for both 2020 and 2030 display similar results, although the low scenario projections for 2030 show a relatively high degree of variation.

A.3. Fuel Cycle

A.3.1. Uranium resources and production

Uranium spot prices continued to slide from approximately US $90/kg U at the beginning of the year to US $70/kg U by the middle of the year, a ten year low. However, by August 2014, the prices started to recover and reached US $115/kg U by November 2014, before easing a little by the end of the year. Even though considerable uranium exploration and development expenditures were reported, many new mining projects have been or are expected to be delayed.

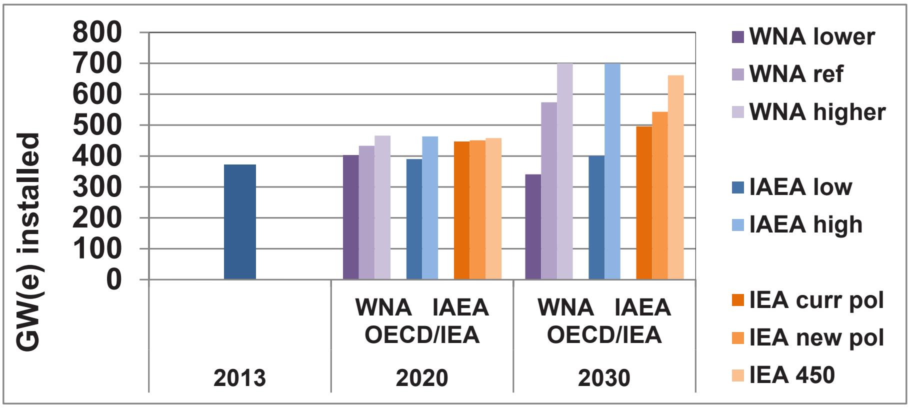

FIG. A.5. Comparison of nuclear power projections from the IAEA [A.2] and the OECD/IEA's 2014 projections [A.5] (based on GW(e) gross), and the WNA's 2013 projections [A.6].

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[3] OECD/IEA figures are based on GW(e) gross.

Unconventional uranium resources further expand the resource base. Current estimates of potentially recoverable uranium as minor by-products are about 8 megatonnes of uranium (Mt U). In 2014, PhosEnergy announced that continuous on-site operation of its PhosEnergy Process Demonstration Plant had demonstrated that high uranium recovery rates (>92%) can be consistently achieved during steady state operations. The Brazilian phosphate/uranium project of Santa Quitéria remains under development and is scheduled to begin production in 2016.

Seawater has been investigated extensively as an unconventional source of uranium. Some 4.5 billion tonnes of uranium, representing an enormous energy resource, are dissolved in the world's oceans at very low concentrations of about 3.3 parts per billion. Research continues into this potential source. Recent advances in research and development (R&D) at the United States Department of Energy (DOE) have led to the reduction of the costs of recovery by about 50%, from US $1230/kg U to US $610/kg U.

Worldwide resources of thorium are estimated to be about six to seven million tonnes. Although thorium has been used as fuel on a demonstration basis, substantial work is still needed before it can be considered for commercial use. A few rare earth element projects, which might produce thorium and thorium containing residues as a by-product, are expected to go into production in the near term, notably at Kvanefjeld in Greenland, (Kingdom of Denmark). Thor Energy continued its five year thorium–mixed oxide (MOX) fuel testing programme in Halden, Norway.

The WNA estimates that uranium production was 58 394 t U in 2012 and 59 370 t U in 2013. In 2014, production capacity was expected to increase by about 7530 t U with the opening of the Cigar Lake mine, Canada, and Four Mile mine, Australia, as well as the initiation of uranium production as a by-product of nickel production at Talvivaara, Finland, and the commissioning of two new in situ leaching (ISL) mines in the United States of America. However, the actual increase will be lower owing to the Talvivaara project being put on hold and a temporary halt in mining operations at Cigar Lake for technological reasons.

The proportion of ISL production, which remains the dominant method, is expected to continue to increase in the medium term. The WNA reports that ISL mining accounted for approximately 46% of world production for 2013, which is mainly from Kazakhstan (38% of total world production in 2013). Owing to unfavourable market conditions, the development of new deposits in Kazakhstan has been put on hold and 2014 production was to be maintained at the 2013 level of 22 500 t U.

The Cigar Lake mine in Canada began production in March. However, owing to continued technological challenges, mining operations were temporarily suspended in July 2014. The mine's annual production capacity is currently

5000 t U/year and is expected to increase to over 8000 t U/year beginning in 2018. The first uranium concentrate from ore mined at the Cigar Lake operation was produced at the McClean Lake Mill in October 2014 (Fig. A.6). The mill is currently seeking approval to increase the licensed capacity to 9200 t U. The application to build and operate a new underground uranium mine as part of the Millennium Uranium Mining Project has been formally withdrawn in the Athabasca Basin of northern Saskatchewan, citing poor world market conditions.

In Namibia, owing to market conditions, all mines and mills that are currently producing are reducing production and, with the exception of Husab, all other mine development projects have been put on hold pending more favourable market conditions. Construction continues on the Husab mine, which is expected to start operation by 2015, with full capacity of 5770 t U possible by 2017. Processing operations resumed at Rössing after a brief disruption due to a leach tank failure. The China National Nuclear Corporation (CNNC) has bought 25% of the Langer Heinrich uranium mine in Namibia.

A new mine in Niger, Imouraren, with a capacity of 5000 t U, which was expected to start production in 2015, will now probably be delayed until 2017 owing to market conditions. The Madaouela Project may go into production as early as 2017 with a capacity to produce 1040 t U/year from 39 600 t U in resources and an additional 11 260 t U from the Miriam deposit, which can be mined as an open pit.

In May 2014, depressed market prices resulted in a halt in production at Paladin's Kayelekera uranium mine in Malawi. Pending an improvement in market prices, production can be recommenced within a lead time of about nine months. The Letlhakane uranium deposit in Botswana is undergoing a detailed

FIG. A.6. In Canada, the McClean Lake Mill produced the first uranium concentrate from ore mined at Cigar Lake. (Photograph courtesy of Cameco Corporation.)

feasibility study, which is on target to be completed in 2015, and first production is anticipated in 2017. A scoping study has been completed for the Reguibat uranium project in Mauritania.

In Australia, Quasar Resources commenced ISL mining operations at the Four Mile East deposits. Western Australia's Environmental Protection Authority recommended state approval for the joint Cameco–Mitsubishi project at Kintyre. A development decision will rest on future market conditions. Processing operations of stockpiled ore restarted in June 2014 at the Ranger mine, which suffered a ruptured leaching tank at the end of 2013. The target date for commencing production from the Ranger 3 Deeps mineralized zone is 2015. Olympic Dam is planning a heap leaching trial of copper and uranium ores as a low cost alternative to the original expansion plan, which was abandoned in 2012.

In the USA, the Lost Creek project in Wyoming started production in 2014. Brazil expects to start a new open pit mining operation at the Engenho deposits in 2015. This mine is expected to produce about 286 t U per year. The ore will be processed in the existing Caetité mill, which is also scheduled for an expansion to produce 670 t U/year in total starting in 2015.

In Turkey, pre-feasibility studies have been completed for the Temrezli ISL project, and the necessary licences have been granted for development. Production is anticipated to commence in 2016 with an annual amount of 385 t U. In April 2014, a generic mining licence was issued for a uranium mine in Retortillo, Spain, which might lead to a nuclear fuel cycle facility licence if its compliance with nuclear regulations is verified during the licensing process. Romania intends to open a new uranium mine in the east of the country, as the resources in the currently operating mine at Crucea are depleted.

Jordan plans to invest US $140 million in a uranium mining project, following an announcement of a reassessment of resources in the central area of the country. The project will have an initial capacity of 300 400 t U/year, expandable to 1500 t U/year, and is expected to be operational in 4–5 years.

In Greenland, (Kingdom of Denmark), a feasibility study is under way to evaluate the production of uranium, rare earth elements and zinc at Kvanefjeld. If the project goes ahead as planned, it is forecast to produce 425 t U/year as a by-product, beginning in 2016.

The Islamic Republic of Iran announced that the Saghand uranium mine is in the final stages of development. Uranium will be mined using open pit and underground methods and the mined ore will be processed at the mill near Ardakan.

The WNA estimates that uranium production in 2014 covered about 92% of the estimated uranium consumption in reactors of 70 015 t U. This is much higher than the past few years, mainly due to the end of a major secondary supply source from military stockpiles, commonly known as the 'HEU deal' or the 'Megatons to Megawatts program' that ended in 2013. The remaining 8% was covered by four secondary sources: stockpiles of enriched uranium, reprocessed uranium from spent fuel, MOX fuel with uranium-235 partially replaced by plutonium from reprocessed spent fuel, and reenrichment of depleted uranium tails. At the estimated 2013 rate of consumption, the lifetime of the 5.9 Mt U estimated total resources economically viable at current market prices would be 84 years.

A.3.2. Conversion, enrichment and fuel fabrication

Six countries (Canada, China, France, the Russian Federation, the United Kingdom and the USA) operate commercial scale plants for the conversion of triuranium octaoxide (U_3O_8) to uranium hexafluoride (UF_6), and small conversion facilities are in operation in Argentina, Brazil, the Islamic Republic of Iran, Japan and Pakistan. A dry fluoride volatility process is used in the USA, while all other converters use a wet process. Total world annual conversion capacity has remained constant at around 76 000 t U as UF_6 per year. Total current demand for conversion services (assuming an enrichment tails assay[4] of 0.25% uranium-235) is in the range of 60 000–64 000 tonnes per year.

AREVA of France is replacing its existing uranium conversion capacity of COMURHEX I, which is scheduled to be shut down in 2015, with the new COMURHEX II project with facilities located at Malvési and Pierrelatte. To upgrade its conversion capabilities, the Russian Federation's TVEL Fuel Company's plans to start constructing a new centre at the Siberian Chemical Complex (SCC) in 2015, with commissioning of the first stage expected in 2018 and the second stage in 2020.

Total global enrichment capacity is currently about 65 million separative work units (SWUs) per year, compared to a total demand of approximately 49 million SWUs per year. Commercial enrichment services are carried out by five companies: the CNNC (China), AREVA (France), the State Atomic Energy Corporation Rosatom (Russian Federation), USEC (USA) and URENCO (both Europe and the USA). There are also small enrichment facilities in Argentina, Brazil, India, the Islamic Republic of Iran, Japan and Pakistan. Argentina is rebuilding its gaseous diffusion capacity at Pilcaniyeu.

[4] The tails assay, or concentration of uranium-235 in the depleted fraction, indirectly determines the amount of work that needs to be done on a particular quantity of uranium in order to produce a given product assay. An increase in the tails assay associated with a fixed quantity and a fixed product assay of enriched uranium lowers the amount of enrichment needed, but increases natural uranium and conversion requirements, and vice versa. Tail assays can vary widely and will alter the demand for enrichment services.

The second phase of the URENCO USA uranium enrichment plant in New Mexico, USA, became fully operational in 2014, with a capacity of 3.7 million SWUs, adding to the first phase of operations that began in June 2010 and reached its full capacity of 1.6 million SWUs in 2012. Construction is already under way on Phase III, which, when completed, by 2022, will bring the total capacity of the plant to approximately 5.7 million SWUs.

URENCO USA is the only operating uranium enrichment plant in the country. Three additional enrichment plants are planned. AREVA is planning to build a 3.3 million SWUs centrifuge plant at Eagle Rock in Idaho. Global Laser Enrichment is planning a 6 million SWUs laser enrichment plant in Wilmington, North Carolina. Both plants are anticipated to start operations before 2020. USEC's American Centrifuge Plant (ACP), which was put on hold in 2009, will start a new R&D programme, the American Centrifuge Technology Demonstration and Operations Program, which will be carried out until the end of 2015. This is intended to maintain the American Centrifuge Project technology and remedy certain technical shortcomings that appeared in the ACP centrifuges in 2014.

The Resende enrichment plant, operated by Brazilian Nuclear Industries (INB), will provide 80% of the enriched uranium needed in 2015 for refuelling of the Angra-1 NPP. INB plans to expand this gradually to 100%. A study on meeting the enrichment needs for all Brazilian nuclear reactors is under way.

Deconversion[5] of depleted UF_6 to uranium oxide or UF_4 is undertaken for long term storage of depleted uranium in a more stable form. Current total world deconversion capacity in 2014 remained at about 60 000 t UF_6 per year. Currently, the main facilities in operation are the AREVA plant in Tricastin, France, two Uranium Disposition Services plants at Portsmouth and Paducah, USA, and the W-ECP deconversion plant at the Zelenogorsk Electrochemical Plant (ECP) in Siberia, Russian Federation. In the USA, a plant in New Mexico operated by International Isotopes is under construction. URENCO ChemPlants, UK, received regulatory and planning approval for a Tails Management Facility in 2010 and expects a 2016 startup. The facility will process URENCO's European inventory of depleted uranium by-products and will comprise a UF_6 deconversion plant and a number of storage, maintenance and residue processing facilities.

The current annual demand for LWR fuel fabrication services remained at about 7000 t of enriched uranium in fuel assemblies, but is expected to increase to about 8000 t U per year by 2015. PHWR requirements accounted

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[5] In order to manufacture enriched uranium fuel, enriched UF_6 has to be reconverted to UO_2 powder. This is the first step in enriched fuel fabrication. It is called reconversion or deconversion.

for 3000 t U per year. There are now several competing suppliers for most fuel types. Total global fuel fabrication capacity remained at about 13 500 t U per year (enriched uranium) for LWR fuel and about 4000 t U per year (natural uranium) for PHWR fuel. For natural uranium PHWR fuel, uranium is purified and converted to uranium dioxide (UO_2) in Argentina, Canada, China, India and Romania.

Having received regulatory approval, China's Tianwan Unit 1, a water cooled water moderated power reactor (WWER), has started using TVEL Fuel Company's new TVS-2M fuel, which allows for an extended use in core for 18 months. This fuel type is already used in the Russian Federation's Balakovo and Rostov NPPs. Tianwan 2 is also due to be converted to use this fuel. TVS-2M fuel for use at Tianwan Units 3 and 4, which are still under construction, will be manufactured at China's Yibin fuel plant.

Thermo-acoustic neutron sensors placed within fuel rod assemblies to monitor core power and temperature distribution are being developed by Westinghouse in the USA. These sensors can help plant operators monitor the core much more accurately, allowing more efficient use of the fuel, and can also monitor defects and safety issues in the fuel rods. The prototype of this device will be tested in 2015, with wider commercial use expected by 2019.

New technology for manufacturing nuclear fuel components from silicon carbide has been developed in Japan by Toshiba and IBIDEN with a view to the development of accident tolerant fuel, inter alia, as a replacement for zircaloy cladding in LWRs. A prototype fuel assembly cover has been developed, and testing in a research reactor will begin in 2016.

Recycling operations provide a secondary nuclear fuel supply by using reprocessed uranium (RepU) and MOX fuel. Currently, about 100 t of RepU per year are produced in Elektrostal, Russian Federation, for AREVA. One production line in AREVA's plant in Romans, France, converts about 80 t of HM of RepU into fuel per year for LWRs in France. Current worldwide fabrication capacity for MOX fuel is around 250 t HM, with the main facility located in France and some smaller facilities located in India, Japan and the Russian Federation.

India and the Russian Federation manufacture MOX fuel for use in fast reactors. A MOX fuel manufacturing facility for the BN-800 fast reactor is under construction at Zheleznogorsk (Krasnoyarsk-26) in the Russian Federation, where there are also pilot facilities in Dimitrovgrad at the Research Institute of Atomic Reactors (NIIAR) and in Ozersk at the Mayak Plant. The MOX fuel fabrication plant at NIIAR has recently undergone modernization and produces vibropacked MOX fuel. The first batch of 56 MOX fuel assemblies has been produced for the Beloyarsk 4 BN-800 fast reactor, which went critical this year. The Atomstroy Research and Design Institute for Nuclear Construction Technology (NIKIMT) has developed and manufactured a remotely operated welding system for producing MOX fuel assemblies. The new system will be used at the MOX fuel fabrication facility in Zheleznogorsk.

Construction has started of a pilot plant for producing fuel for the experimental BREST-300 fast reactor to be built at the SCC in the Russian Federation. The testing of the TVS-5 fuel assembly with mixed uranium–plutonium nitride fuel has also been completed (Fig. A.7). Construction of BREST-300 is planned to start in 2016 and is expected to be completed in 2020. BREST-300 is a lead cooled reactor system developed by the Research and Development Institute of Power Engineering (NIKIET).

In the USA, the construction licence for the partially built MOX Fuel Fabrication Facility at the Savannah River Site in South Carolina has been extended by ten years and funding for continuing construction was approved by the US Congress.

A.3.3. Assurance of supply

In December 2010, the Board of Governors approved the establishment of an IAEA LEU bank in Kazakhstan. Since then the IAEA's Secretariat has worked on the financial, legal and technical arrangements for establishing the bank. This has included a comprehensive technical assessment of the facility proposed to contain the IAEA LEU Bank. In 2014, the programmatic impact of seismic safety on the overall IAEA LEU Bank project was assessed to determine whether the geological fault that exists in close proximity to the proposed IAEA LEU Bank site

FIG. A.7. TVS-5 fuel assembly, the prototype fuel for the advanced BREST-300 reactor. (Photograph courtesy of SCC.)

has the potential to affect the safety of the IAEA LEU Bank. This programmatic risk assessment (PRA), as independently reviewed by an international seismic engineering consultancy, concluded that the seismic safety of the IAEA LEU Bank could be ensured through appropriate engineering measures, even in the extreme seismic event scenario posited for the PRA. Based upon the outcome of the PRA, the IAEA and Kazakhstan concluded with confidence that the IAEA LEU Bank can be established at the Ulba Metallurgical Plant (UMZ) site. An LEU reserve in Angarsk, established following the February 2011 agreement between the Government of the Russian Federation and the IAEA, remained operational.[6]

A.3.4. Back end of the nuclear fuel cycle

Two different strategies are used for the management of spent fuel from power reactors. Either the spent fuel is stored and subsequently reprocessed to extract usable material (uranium and plutonium) for fabrication of new fuel or it is stored pending disposal in a deep geological repository. Recycling through reprocessing enables a decrease in the amount (volume) of HLW that will eventually be disposed of, and maximizes the use of the fissile materials for energy production. Currently, countries such as China, France, India, the Russian Federation and the UK reprocess spent fuel, while other countries, such as Finland and Sweden, have opted for the disposal of spent fuel in a voluntary host community. Most countries have not yet decided which strategy to adopt and are currently storing spent fuel and keeping abreast of developments associated with both strategies.

The EU Council Directive 2011/70/Euratom [A.8] legally binds EU Member States to establish and maintain a spent fuel and radioactive waste management policy. It indicates the rules that have to be followed by each EU Member State regarding national framework, competent regulatory authority, licence holders, expertise and skills, finance resources, transparency and reporting, among others. Each EU Member State shall have ultimate responsibility for managing the spent fuel and radioactive waste generated within it. In 2014, the European Academies' Science Advisory Council (EASAC) published Management of Spent Nuclear Fuel and its Waste, a report to inform policymakers on important issues to take into consideration in developing relevant national programmes. The report concludes that fuel cycle policy should consider: (i) long timeframes (more than 100 years) of all fuel cycles, and that therefore it is advantageous to generate robust technical solutions, covering the whole process, but keeping alternatives

[6] Other assurance of supply mechanisms currently in place are described in Ref. [A.7].

available to accommodate changes in future policies and plans; (ii) flexibility in future choices; (iii) potential improvement from recycling in fast neutron reactors; (iv) national or regional solutions for deep geological disposal; and (v) education and training necessary to support the long term safe management of spent nuclear fuel.

The DOE Office of Nuclear Energy released in 2014 the final report of a study on nuclear fuel cycle evaluation and screening. The three year study defined a framework (a logical structure and process that includes sets of data, methods and tools) to support decision making in nuclear fuel cycle R&D. It identified the four most promising options — all continuous recycle fuel cycles using fast reactors with uranium based fuel — and the R&D required for these fuel cycles, as well as 14 other potentially promising fuel cycles that may improve performance.

The USA approved a new regulation in 2014, the Continued Storage of Spent Nuclear Fuel Rule, under which spent fuel can be safely stored in spent fuel pools and dry casks beyond the licensed life of a reactor, until permanently disposed of in a deep geological repository. The new rule and its associated Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel replace the 2010 Waste Confidence Decision and Temporary Storage Rule. The US Nuclear Regulatory Commission (NRC) will resume licensing of new reactors and processing licence renewals for old ones, which remained suspended for two years pending the new regulation.

In the Republic of Korea, an independent panel of experts provided a report to the Public Engagement Commission on Spent Nuclear Fuel Management (PECOS) recommending researches on various medium and long term spent nuclear fuel management methods, including permanent disposal, recycling, reprocessing and storage. The panel also recommended building new interim spent fuel storage facilities using dry storage in a timely manner. PECOS is an interim consulting body established in 2013 to obtain expert advice on various ideas for spent fuel management, and is scheduled to submit its policy recommendations to the Government by June 2015.

In 2014, about 10 000 t HM were discharged as spent fuel from all NPPs. The total cumulative amount of spent fuel that has been discharged globally is approximately 380 500 t HM, of which about 258 700 t HM are stored in facilities at either at-reactor or away-from-reactor sites. Less than a third of the cumulative amount of spent fuel discharged globally has already been reprocessed. In 2014, the global commercial reprocessing design capacity, spread across five countries (France, India, Japan, the Russian Federation and the UK), was about 4800 t HM per year. However, not all this capacity is operational.

In 2014, the Magnox reprocessing plant (Fig. A.8) in Sellafield, UK, celebrated 50 years of operations. The plant has so far reprocessed more than 50 000 tU, as much as all the other plants put together. It is expected to end operations in 2017.

FIG. A.8. The Magnox reprocessing plant in Sellafield completed 50 years of operation. (Photograph courtesy of Sellafield Ltd.)

The Rokkasho Reprocessing Plant in Japan, due to be completed in 2014, will be delayed until 2016 to meet national regulatory requirements.

The centralized dry spent fuel storage facility at Zheleznogorsk, Russian Federation, which began operations in 2012, is currently being expanded. In total, there will be three buildings with a capacity of around 30 000 t U for high power channel type reactor (RBMK) and WWER spent fuel. The second stage for WWER spent fuel storage is to be commissioned in 2015. The RT-2 reprocessing plant is expected to be operational by 2021 for reprocessing WWER-1000 fuel.

A framework joint venture agreement was signed in 2014 between China’s CNNC and Canada’s Candu Energy to build Advanced Fuel CANDU Reactors (AFCRs). The AFCR will be designed to use recycled uranium or thorium as fuel, thus reducing spent fuel inventories and significantly reducing the fresh uranium required. Spent fuel from four conventional PWR reactors can fully supply one AFCR unit (as well as providing recycled plutonium for MOX).

Ukraine started constructing a Central Spent Fuel Storage Facility, which will provide away from reactor site storage for spent fuel produced by the

WWER-1000 and WWER-440 reactors located at the South Ukraine, Rovno and Khmelnitski sites. The facility will be located between the resettled villages of Stara Krasnytsya, Buryakivka, Chystohalivka and Stechanka, within the Chernobyl Exclusion Zone, and will facilitate the ecological rehabilitation of the Exclusion Zone and the renewal of economic activities on some land within this zone. This facility is expected to be operational by 2017.

The removal of all 1331 spent fuel assemblies stored in the spent fuel pool at Unit 4 of the Fukushima Daiichi NPP was completed on 5 November 2014. The spent fuel has been transferred to the common spent fuel pool located at the reactor site, from which older assemblies are transferred to dry storage in metal casks at the reactor site.

A.3.5. Decommissioning, remediation and radioactive waste management

The use of nuclear technologies of any kind — for energy production, research activities, medical and industrial applications — carries with it an obligation to safely manage resulting radioactive waste, as well as planning for associated future decommissioning and environmental remediation activities. Understanding the current radioactive waste inventory status, i.e. its volumes, locations, conditions and properties, as well as future waste generation trends, is of paramount importance to adequately plan the required waste management facilities and activities. The safe management of radioactive waste requires adequate management of waste streams, their treatment and conditioning, as well as providing adequate storage capacities, transport between facilities, and ultimately, disposal.

The Scientific Forum, held during the 58th session of the IAEA's General Conference, emphasized the need for a comprehensive, integrated, cradle to grave approach for radioactive waste management, and highlighted that solutions are available for implementation (Fig. A.9).

A.3.6. Global radioactive waste inventory estimates

Global radioactive waste inventory estimates are based on Member States' voluntary information to the IAEA's Net Enabled Waste Management Database (NEWMDB) (Table A.2 [A.9]). The IAEA has launched a status and trends project in cooperation with the European Commission and the OECD/NEA to develop an accurate, streamlined national reporting procedure that can be used for all Member States' reporting obligations. Consistent with this, the NEWMDB is being improved to allow for more accurate estimates of global inventories.

FIG. A.9. Practically all Member States have to manage some form of radioactive waste. (Legend: Orange: Member States whose inventories predominantly originate from nuclear power production. Blue: Member States whose inventories predominantly originate from research reactors. Green: Member States whose inventories predominantly consist of disused sealed radioactive sources.)

As of December 2014, 467 storage facilities and 154 waste disposal facilities for the management of these waste inventories were operating, suspended or closed worldwide [A.9].

A.3.7. Decommissioning

As of 31 October 2014, there are 438 NPPs in operation around the world, and a further 149 that are shut down or are undergoing decommissioning, including 17 that have been fully decommissioned. There are also a large number of fuel cycle facilities: more than 300 in operation, about 170 that have been shut down or are undergoing decommissioning, and 125 that have been fully decommissioned. As for research reactors, 247 are operational, more than 180 have been shut down or are undergoing decommissioning, and more than 300 research reactors and critical assemblies have been fully decommissioned.

TABLE A.2. ESTIMATE OF GLOBAL RADIOACTIVE WASTE INVENTORY FOR 2014 *(based on Member States' voluntary information to the NEWMDB [A.9].)*

Waste class	Storage (cubic metres)	Cumulative disposal (cubic metres)
Very low level waste (VLLW)	73 000	273 000
Low level waste (LLW)	56 703 000	65 192 000
Intermediate level waste (ILW)	8 745 000	10 589 000
High level waste (HLW)	2 745 000	72 000

Note: Source: NEWMDB (2013), official national reports and publicly available data. The figures in Table A.2 are estimates and are not an accurate account of radioactive waste quantities currently managed worldwide. Recent updates are based on prior reports of both the inventories and the expected annual waste arising. There are also inherent differences in the estimated storage quantities from year to year due to (a) mass and volume changes during the waste management process; (b) changes in reporting and changes or corrections made by Member States to their own data; and (c) the addition of new Member States to the database. Wastes are typically treated and conditioned and taken through various handling steps during storage and prior to disposal. Therefore, the mass and volume of radioactive waste are continuously changing during the process of predisposal management. This can lead to discrepancies in estimated storage quantities from year to year.

A significant level of decommissioning experience has been gained since the turn of this century, with the greatest progress achieved mainly in countries with long running nuclear power programmes, particularly in France, Germany, the Russian Federation, Spain, the UK and the USA. Examples of programmes with substantial progress in decommissioning in 2014 include: the ongoing progress in the dismantling of the first generation of NPPs in France; the ongoing progress with the segmenting and conditioning of waste from a reactor at the José Cabrera NPP in Spain; the removal of filter galleries from the Windscale Pile 1 chimney in the UK, which was contaminated during the pile fire in 1957 (Fig. A.10); and the three active NPP decommissioning programmes in the USA. Similar projects are also proceeding in Bulgaria, Lithuania and Slovakia, where NPPs were shut down before the end of their design lives.

Given that many of the nuclear facilities currently in operation were commissioned during the 1970s and 1980s and will reach the end of their design lives within the next two decades, significant decommissioning activities are expected for several decades to come.

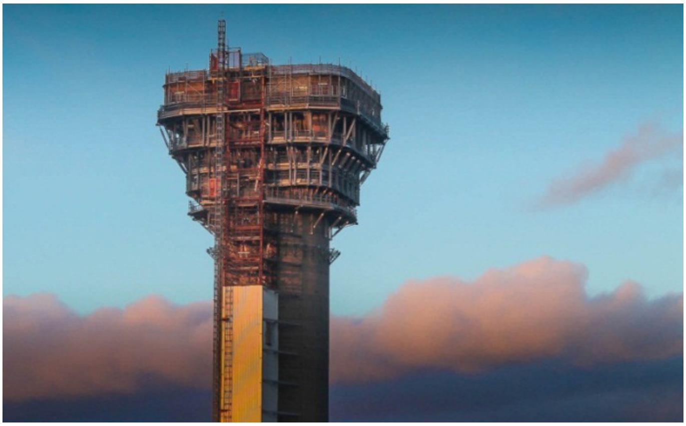

FIG. A.10. Decommissioning of the filter galleries from the Windscale Pile 1 chimney, (Photograph courtesy of Sellafield Ltd.)

Activities contributing to the decommissioning of NPPs that have been shut down after a nuclear accident are challenging for several countries, including Japan (Fukushima Daiichi — see page 33) and Ukraine (Chernobyl). Significant progress was achieved at the Chernobyl NPP with the installation of a New Safe Confinement (NSC) construction. The NSC should be fully installed to cover the damaged Unit 4 in 2015 with the primary goal being to prevent the release of radioactive material into the environment and to allow a future partial demolition of the old structures.

A.3.8. Remediation

Some countries are moving forward in dealing with the remediation of land affected by past practices and accidents and have accordingly built up appropriate technical resources and expertise. Many national programmes, however, still face significant challenges that are impeding the implementation of remediation programmes. The baseline report under the Constraints to Implementing Decommissioning and Environmental Remediation (CIDER) Project, launched in 2013 to help overcome these constraints, has been finalized. It identified barriers in four major categories: (i) national policy, legal and regulatory framework, (ii) financial constraints, including logistics, resources and management of available funds, (iii) technology and infrastructure impediments, (iv) stakeholder issues that need to be addressed and emphasized throughout the lifecycle of the planning and implementation of decommissioning and environmental remediation projects. To overcome some of these barriers, the baseline report also identified strategies that can benefit from greater collaboration between programmes. However, further innovative solutions are also needed.

One significant achievement has been the development of the Mobile Unit for Site Characterization. This mobile laboratory concept provides an interactive capability to perform rapid and effective site characterization, with immediate real time identification of areas of high interest. Such a unit can be an asset to Member States that do not have an adequate analytical laboratory infrastructure. It can also help those that have analytical laboratory capabilities, but may be faced with large, unforeseen characterization challenges. Making the unit available to Member States is an effective way to support characterization of contaminated sites, which is a crucial step in the implementation of a remediation project.

Addressing the consequences of the Fukushima Daiichi accident: Radioactive waste management, decommissioning and remediation

The Fukushima Daiichi accident created significant challenges related to decommissioning, remediation and radioactive waste management, both on-site and spread over a vast area off-site. Cooperating with the international community and seeking advice from international review missions under the auspices of the IAEA, Japan has achieved good progress in these areas.

The management of the remaining fresh and spent fuel is one of the most important activities towards decommissioning the NPP. Removing the spent and fresh fuel from the fuel pool at Unit 4 to the common pool on-site was an important task implemented during the course of the year.

Progress continues with the deployment of liquid waste treatment technologies to remove radionuclide contaminants from the nearly 400 000 tonnes of radioactive water collected at the facility. Caesium is currently removed using two different ion exchange systems, while the Tokyo Electric Power Company (TEPCO) has recently commissioned a strontium removal system configured into a mobile and transportable form that can be installed directly at locations where the waste is generated or stored. Improvements have also been made in the performance of the Multi-Radionuclide Removal System, for removing strontium and other radionuclides remaining after caesium removal. By increasing the current 750 m^3/d capacity to 2000 m^3/d, TEPCO expects to accelerate the decontamination of the continually accumulating contaminated water. This year, the Mitsubishi Research Institute has been charged with exploring new advanced in situ technologies to decontaminate caesium and strontium from harbour seawater.

The remediation works have shown good progress. Also, there has been good coordination between remediation activities and reconstruction and revitalization efforts. Lessons learned from the remediation works are being accumulated, and sharing them with the international community is of paramount importance. They include the promotion of radiation protection of the public, focusing on individual dose rates; the enhancement of risk communication by conveying clear messages and new findings on the effects of decontamination; improvement in the efficiency and effectiveness of decontamination activities; and the enhancement of comprehensive policies to protect individuals against the undesired effects of ionizing radiation while addressing the anxiety of the public and restoring their sense of safety.

The Fukushima Prefecture government agreed to host an interim storage facility at a site close to the Fukushima Daiichi site. This will allow radioactive waste and contaminated soil from nearly 1000 temporary storage sites to be transferred to and consolidated at one place.

A.3.9. Legacy radioactive waste

The IAEA's Contact Expert Group for International Nuclear Legacy Initiatives in the Russian Federation (CEG) contributed to the successful implementation of international programmes in this area. To date, 197 decommissioned nuclear submarines have been defuelled and dismantled by the Russian Federation and its international partners. The defuelled submarine reactor units are in the process of being sealed and 76 have been placed in long term storage facilities in the north-west and the far east of the country. Construction of a regional centre for conditioning and storage of all legacy radioactive waste in the north-west region (Fig. A.11) was completed in December 2014 with assistance from Germany. Technologies have been developed for the safe defuelling of reactor cores that have liquid metal coolant and their subsequent storage. A hot cell for the treatment of defective spent nuclear fuel canisters was commissioned at Mayak with assistance from France. Joint international efforts for decommissioning powerful radioisotope thermoelectric generators that were used at lighthouses along the coastline of the Russian Federation are nearing successful completion. A December 2014 review between the IAEA and the CEG Chairman foresaw the completion of CEG activities by summer 2015.

FIG. A.11. The Regional Centre for Radioactive Waste Conditioning and Long Term Storage in the north-west part of the Russian Federation (left) and the storage pad for reactor units (right). (Photograph courtesy of Energiewerke Nord GmbH.)

A.3.10. Radioactive waste treatment and conditioning

Once generated, radioactive waste must be reduced in volume and converted into a form that is acceptable for safe storage and disposal, and allow for handling and transport.

Treatment technologies for solid, liquid and gaseous wastes are well established and operational in many Member States. A novel fluidized-bed steam reforming technology is currently at the commissioning stage at the DOE Idaho National Laboratory (INL) site to treat the approximately 3 300 000 litres of highly radioactive liquid waste from the reprocessing of HEU fuel. The use of plasma treatment for solid waste, which results in a high volume reduction factor, is becoming more widespread, and a plasma treatment facility is currently under construction at Bulgaria's Kozloduy NPP.

Waste conditioning includes the immobilization of radionuclides, placing the waste into containers, and providing additional packaging. Geopolymer matrices continue to show promise for the immobilization of difficult waste streams such as the spent organic ion exchange resins at the Bohunice waste treatment plant in Slovakia. High level radioactive wastes need highly durable waste forms and are usually vitrified. However, an alternative conditioning technique, hot isostatic pressing, has been recommended to produce the waste form for disposal of the 4400 m^3 of HLW calcine currently stored at the INL site. In Australia, plans are under way to construct a facility to treat waste from the past, current and future manufacture of molybdenum-99 and other isotopes used in medical applications. This plant will calcine the liquids and immobilize radioactive waste in a durable solid rock-like material (synroc) suitable for storage and disposal.

In legacy facilities, notable progress was made at Sellafield, UK, with the commencement of repackaging of legacy canned fuel from the Pile Fuel Storage Pond, resuspension of radioactive sludge in the First Generation Magnox Storage Pond, and opening of the new Encapsulated Product Store 3 for the storage of ILW.

A.3.11. Radioactive waste disposal

Disposal facilities for all categories of radioactive waste, except HLW and/or spent fuel, are operational worldwide. These include trench disposal for VLLW (e.g. in France, Spain, Sweden and the USA) and for LLW in arid areas (e.g. in Argentina, India, South Africa and the USA); near surface engineered facilities for LLW (e.g. in China, the Czech Republic, France, India, Japan, Poland, Slovakia, Spain and the UK); sub-surface engineered facilities for low and intermediate level waste (LILW) (e.g. in Finland and Sweden); borehole disposal of LLW in the USA; and geological facilities to receive LILW (e.g. in Hungary and the USA). Disposal options for naturally occurring radioactive material waste vary according to national regulations and range from trench disposal facilities to sub-surface engineered facilities (e.g. in Norway).

Steps have been taken towards the licensing of geological disposal facilities for HLW and/or spent fuel in Finland, France and Sweden.

Canada is advancing work on the development of two deep geological repositories (DGR). Ontario Power Generation, Canada's largest nuclear utility, is proposing to build a DGR for its LLW and ILW at the Bruce nuclear site in Kincardine, Ontario. This project is currently undergoing a federal regulatory review process. The Nuclear Waste Management Organization (NWMO), an organization of Canada's nuclear utilities established pursuant to the 2002 Nuclear Fuel Waste Act, is working with 11 interested communities through a siting process to identify a willing community, with a safe and suitable site to host a DGR for the long term management of the nation's nuclear fuel waste.

China foresees geological disposal needs deriving from the reprocessing of 140 000 tonnes of spent fuel from a fleet of 48 reactors. Disposal is to be sited in either a crystalline or a sedimentary host formation, and construction of the first underground research facility (URF) is planned in the Beishan area. The results expected from this URF will contribute to informing future decisions on deep geological disposal implementation.

The French National Radioactive Waste Management Agency (Andra) has assessed the results of the formalized national public stakeholder engagement process conducted in 2013, as well as feedback obtained from its regulator. It plans to submit a licence application in 2017 and plans to have greater involvement of stakeholders in its decisions and, in particular, in its operations master plan.

To implement its repository site selection act of June 2013 for the disposal of heat emitting radioactive waste, Germany established a new commission in 2014. Its recommendations, expected by 2016, should include site selection criteria and requirements for stakeholder participation.

In 2014, the UK Government issued a White Paper entitled Implementing Geological Disposal, which describes a framework for the long term management of higher activity radioactive waste. It outlines an approach to identifying potential sites for a geological disposal facility that is based on working with interested communities, beginning with two years of actions to address issues that stakeholders had stated were important to them.

In the USA, there were several significant developments reported in 2014 in the field of geological disposal. In its Safety Evaluation [A.10], the NRC found, with reasonable expectation, that the DOE has demonstrated compliance with the NRC regulatory requirements for post-closure safety.

The Blue Ribbon Commission on America's Nuclear Future recognized the possible role that the deep borehole disposal concept could play in the safe and effective disposal of nuclear materials. The concept foresees the drilling of a borehole (or array of boreholes) into crystalline basement rock to a depth below surface of about 5000 m. The DOE is proposing to conduct a demonstration.

In addition, the operations of the DOE's Waste Isolation Pilot Plant (WIPP) have come under scrutiny by its regulator, the US Environmental Protection Agency (EPA), after two unrelated events (Fig. A.12). The first one, a truck fire, had no radiological consequences. The investigation identified a lack of routine maintenance and proper sub-surface work safety culture and the need for corrective actions related to operational safety. A second event is believed to have been caused by an incompatible mix of wastes and resulted in a radioactive release due to an exothermic reaction in a disposed waste container. The resulting exposures were well below the EPA's Clean Air Act regulatory limit. The DOE published a WIPP recovery plan, aimed at resuming limited disposal operations in the first quarter of 2016.

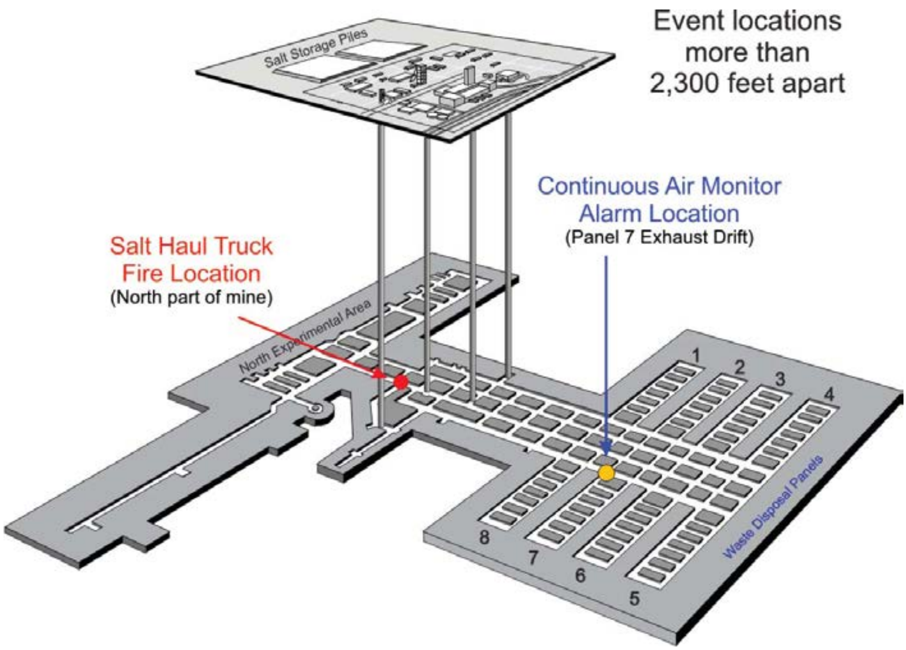

FIG. A.12. Locations of the two events at WIPP in 2014. (Graphic courtesy of WIPP, US Department of Energy.)

A.3.12. Management of disused sealed radioactive sources

Disposal options for disused sealed radioactive sources (DSRSs), including co-disposal with other waste at suitable facilities, increased number of recycling and repatriation options, or disposal in dedicated boreholes, are under serious consideration in several countries, including Ghana, Malaysia, the Philippines and South Africa. A generic safety case has been developed for borehole disposal of Category 3–5 sources, and is under development for Category 1 and 2 sources.

A number of successful operations have been conducted in 2014 to remove DSRSs from user premises and bring them under control by moving them either to a national radioactive waste storage facility or to another institution with proper storage conditions. A mobile hot cell was deployed in Costa Rica to condition and remove five high activity DSRSs for recycling. Five high activity Category 1 and 2 DSRSs in Morocco were consolidated and repatriated to France. The repatriation of disused French manufactured Category 1 and 2 sources was initiated in several Member States, including Cameroon and Lebanon, with the repatriations scheduled for first half of 2015.

Good progress was made to link the mobile hot cell to a design concept for borehole disposal, with the intent of minimizing the handling of sources and preventing unnecessary transport.

Operations involving the conditioning of such sources were completed in Fiji, Malaysia and Montenegro, and local and regional personnel were trained.

The IAEA extended access to the International Catalogue of Sealed Radioactive Sources and Devices to many individual country nominees, thereby facilitating the identification of DSRSs found in the field. Efforts to add more details on sources and devices were initiated in 2014, to improve the usefulness of the catalogue.

A.4. Safety

Safety improvements continued to be made 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. The actions carried out by Member States in the light of the accident were also reviewed during the Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety, held in Vienna from 24 March to 4 April 2014.

The IAEA Action Plan on Nuclear Safety remained at the core of the actions taken by Member States, the Secretariat and other relevant stakeholders to strengthen nuclear safety framework. The IAEA continued to share and disseminate the lessons learned from the accident through the analysis of relevant technical aspects. It organized international experts meetings on radiation protection after the Fukushima Daiichi accident (17–21 February) and on severe accident management (17–20 March). In addition, the IAEA held the International Conference on the Challenges Faced by Technical and Scientific Support Organizations (TSOs) in Enhancing Nuclear Safety and Security (27–31 October). In 2014, the IAEA Report on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [A.11] and the IAEA Report on Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding [A.12] were published.

The operational safety of NPPs remains high, as indicated by safety indicators collected by the IAEA and the World Association of Nuclear Operators. Figure A.13 shows the number of unplanned manual and automatic scrams or shutdowns per 7000 hours (approximately one year) of operation. Scrams are only one indicator of safety performance but this approach is commonly used

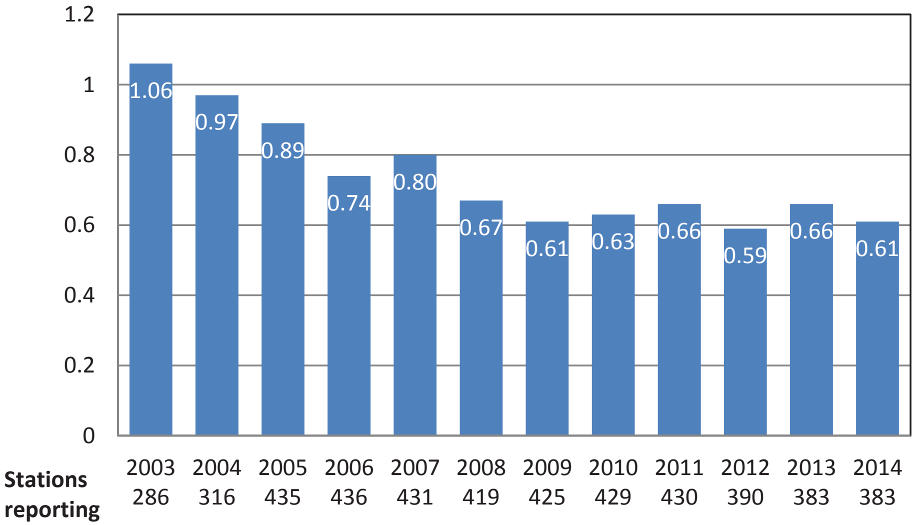

FIG. A.13. Mean rate of scrams: the average, annual number of automatic and manual scrams.(Source: Ref. [A.1].)

as an indication of success in improving plant safety by reducing the number of undesirable and unplanned thermalhydraulic and reactivity transients requiring reactor scrams. As shown, steady improvements continue, with some slight upward trend in 2013.

Additional information on nuclear safety can be found in the Nuclear Safety Review 2015 [A.13].

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B. ATOMIC AND NUCLEAR DATA

The continuously updated files at the world's four core nuclear data centres are the basis of all nuclear science and technology for both power and non-power applications. These centres are the IAEA's Nuclear Data Section (NDS), the US National Nuclear Data Center at Brookhaven National Laboratory, the OECD/NEA Data Bank, and the Russian Nuclear Data Centre in Obninsk. The NDS coordinates two networks that link these and other specialized centres: the International Network of Nuclear Reaction Data Centres, which primarily deals with the Experimental Nuclear Reaction Data database, and the International Network of Nuclear Structure and Decay Data Evaluators, which oversees the Evaluated Nuclear Structure Data File.

The collaborative nature of nuclear data work is illustrated by the Working Party on International Nuclear Data Evaluation Co-operation (WPEC) established by the OECD/NEA. For 25 years, the WPEC has used subgroups to tackle specific issues such as the CIELO. The CIELO project brings together experts from across the international nuclear reaction data community to identify and document discrepancies between existing evaluated data libraries, measured data, and model calculation interpretations, and aims to make progress in reconciling these discrepancies to create more accurate evaluations for all applications. The initial focus is on a small number of the highest priority nuclei, namely, hydrogen, oxygen, iron and the major actinides. Another WPEC subgroup is dealing with a proposal for a new modern structured data format in Extensible Markup Language (XML).

Another area of international collaboration is in experimental facilities. The pulsed neutron source at the European Organization for Nuclear Research (CERN) neutron time-of-flight facility (n_TOF) has measured many cross-sections over a wide energy range that are needed for stellar nucleosynthesis, symmetry breaking effects in compound nuclei, the investigation of nuclear level densities, and applications of nuclear technology, such as the transmutation of nuclear waste, accelerator-driven systems and nuclear fuel cycle investigations (Fig. B.1). A consortium of European nations has started the construction of one of Europe's largest active infrastructure projects, the European Spallation Source (ESS). The foundation stone of the ESS was laid in October 2014 in Lund, Sweden, with the first neutrons expected to be generated in 2019.

Radioactive ion beam (RIB) facilities make it possible to measure many nuclides that cannot be studied in conventional facilities. Several domains of research in nuclear physics at the limits of stability can be investigated using such beams, including the study of nuclei created by the r and rp processes, shell closure in the vicinity of magic numbers and the investigation of very heavy

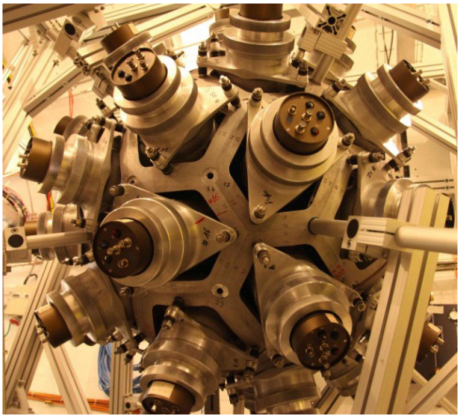

FIG. B.1. Detectors at the n_TOF facility at CERN. (Photograph courtesy of CERN.)

elements. The Spiral-2 facility being built at the National Large Heavy Ion Accelerator research centre in France will enable a large number of international research workers to have access to RIBs; the first experiments are planned for 2015.

The proceedings of the International Conference on Nuclear Data for Science and Technology, held in 2013 in New York, USA, were published in a peer reviewed journal [B.1] in 2014. This triennial conference showcased the work of several hundred scientists and engineers involved in the production or use of nuclear data for many applications.

The applications that rely heavily on nuclear data are: fission reactors, the focus of the CIELO project; fusion research, particularly that taking place as part of the International Thermonuclear Experimental Reactor; medical needs, particularly isotope production; and dosimetry, where properties of the neutron spectrum can be measured using a range of very well characterized reaction cross-sections.

Atomic data are usually seen as a separate area of work, but one topic in which atomic and nuclear data extensively interact is nuclear moments. Experimental atomic fine structure spectroscopy, in combination with precise atomic structure calculations, provides a probe for nuclear structure parameters, including the charge radius, magnetic dipole moment and electrostatic quadrupole moment. Detailed quantum electrodynamics calculations, generally for helium-like heavy ions, are now making it possible to separate field-theoretical and Bohr–Weisskopf effects on the hyperfine structure. Several applications of this nature were described at the Ninth International Conference on Atomic and Molecular Data and their Applications held from 21–25 September 2014 in Jena, Germany.

The science of uncertainty quantification (UQ) has expanded rapidly in applications for the simulation of complex systems such as weather and climate. In 2013 and 2014, several meetings addressed the newly developing application of UQ to calculated atomic and molecular data; this has been done for experiments. This application is concerned with simple physical systems for which accurate calculations are extremely challenging and it represents to some extent a new branch of the science of UQ.

New soft and hard X ray free electron laser (XFEL) user facilities are coming on-line around the world. Two hard XFEL facilities are in operation: the Linac Coherent Light Source at Stanford, USA, was commissioned in 2009, and the SPring-8 Angstrom Compact Free Electron Laser facility at Harima, Japan, in 2011. The hard X ray facilities PAL-XFEL at Pohang Accelerator Laboratory in Pohang, Republic of Korea, the European XFEL in Hamburg, Germany (Fig. B.2) and the SwissFEL in Villigen, Switzerland, are under construction. The first two are expected to produce first laser light in 2016. The status of these facilities and of other free electron lasers around the world was reviewed at the 36th International Free Electron Laser Conference held in Basel, Switzerland, in August 2014. These XFELs are used to study the electronic properties of atoms, molecules and materials, including the study of fast processes in complicated biological molecules such as DNA.

FIG. B.2. The European XFEL is located in Hamburg, Germany. (Photograph courtesy of European XFEL.)

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C. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

C.1. Accelerators

In 2014, two ambitious and large scale accelerator projects were started that are both scheduled to be operational by 2020–2022. The European Synchrotron Radiation Facility in Grenoble, France, has started the upgrade of its current accelerator based photon source. The new source, considered to be the fourth generation of its kind, will be brighter (one million times in performance enhancement) compared to the existing source, while reducing energy consumption by 20%. It is aimed at providing a variety of capabilities for researchers across a broad range of disciplines, such as physics, chemistry, materials science and biology. The construction of the ESS particle accelerator has also started, which will provide the most intense pulsed neutron beams in the world for scientific research. The ESS will be an accelerator based facility for materials science research using neutron scattering. It will provide neutron beams up to 30 times brighter than any current neutron source. It is located in Lund, Sweden, near the MAX IV Laboratory, which will complement the ESS in materials science research.

Synchrotron facilities are important research tools and valuable facilitators of technological development. The beam time at synchrotron facilities is typically oversubscribed by a factor of 2–3, i.e. only a third to half of all research proposals can be approved and realized. At particularly modern beamlines, e.g. at free electron lasers, this factor is even higher and is around 5. This makes it difficult, if not impossible, for research groups that are newcomers in the field and that are from developing Member States to gain access to beam time at a synchrotron facility.

To address this situation and to be able to provide access to a state of the art synchrotron facility for research groups from any Member State, the IAEA has set up a multitechnique experimental facility as an end station of the X ray fluorescence (XRF) beamline at the Elettra facility in Trieste, Italy (Fig. C.1). The project was carried out in cooperation with Germany’s Federal Institute of Physics and Technology and the Technical University of Berlin.

The IAEA’s UHVC beamline end station allows a synergistic application of different XRF and spectrometry methodologies, offering a complete elemental, chemical and structural characterization of materials. The UHVC is equipped with an advanced 7 axis motorized sample manipulator to move/rotate the sample to be investigated and the X ray detectors in various orientations with respect to the synchrotron beam. The optimum features of the XRF beamline include an

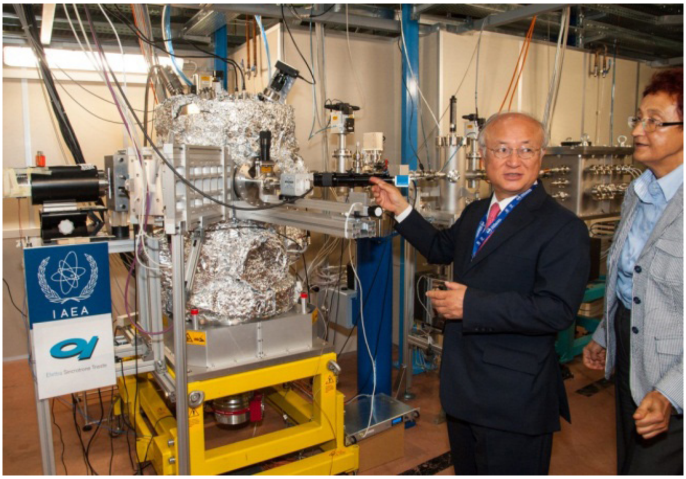


FIG. C.1. IAEA Director General Yukiya Amano and Elettra Research Coordinator Maya Kiskinova with the ultra high vacuum chamber (UHVC) during the opening of the new XRF beamline, 6 October 2014. (Photograph courtesy of Elettra.)

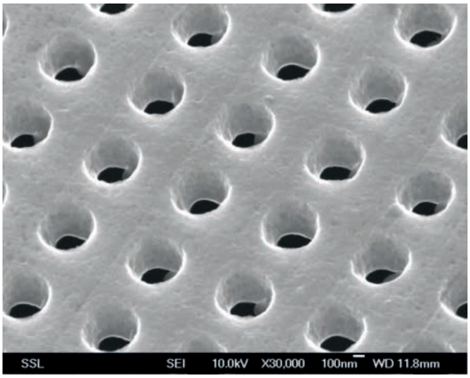
extended energy tunability (2–14 keV), flux (5109 photons per second at 5.5 keV, 2.4 GeV machine mode), resolving power of 1.5×10^{-4}, small beam divergence (0.15 mrad) and beam size at the exit slits equal to 220 µm × 90 µm.

In 2014, the IAEA also launched the Accelerator Knowledge Portal (AKP) [C.1], a new web site designed to bring together the accelerator community and to provide references for stakeholders such as policy makers, science research councils and governmental organizations dealing with human and scientific research infrastructures. The portal includes a database of 196 operational low and medium energy particle accelerator facilities worldwide. Designed to be an attractive platform for scientific collaboration and networking, it gathers links for software and databases, scientific and educational documents, the latest highlights of accelerator based research, and announcements of conferences, workshops and schools, and allows registered users to upload their contributions.

The management of an accelerator facility includes a number of challenges that are different from other research facilities. As accelerators are often both the tools and the objects of research, these aspects can easily be overlooked. To assist Member States in efficiently responding to the current economic and technical challenges, the IAEA organized, jointly with the SOLEIL synchrotron, a Technical Meeting on Management Strategies for Accelerator Facilities, held 15–19 September 2014 in Saint-Aubin, France.

Single ion sources capable of implanting ions with nanometre precision have recently become the driving force for several research areas and possible developments of novel technologies. As part of an IAEA coordinated research project on radiation induced defects in semiconductors and insulators, single ion irradiation was used to evaluate the transport properties of charge induced defects in electronic devices damaged by radiation. Current transients induced by single ions reflect the properties of the material, as well as the structure of the device, and also depend on the type of ion. Single ions can also modify the electrical, optical and structural properties of a material at the point of ion entry into the material and along the ion track. Deterministic single ion irradiation/implantation is a challenging but important technology that can open the door to precise position controlled material modification.

The two images in Fig. C.2 show examples of such modified materials. The left image shows a process that can be used to micromachine silicon with feature sizes down to tens of nanometres, allowing the fabrication of a range of new nanoscale structures for use in fields such as micro/nanofluidics and nanoimprint lithography [C.2]. The right image shows how single ion implantation can be used for defect engineering of diamonds to create nitrogen-vacancy centres, which are expected to have a promising application for quantum computing, magnetic sensors with extremely high resolution or nanolevel photonics [C.3]. Because material properties can be modified along the ion track, the single ion irradiation technique with nanometre level position control is a key technology for modifying the electrical, optical and structural properties of materials.



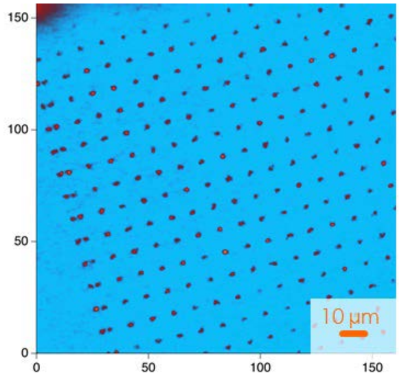


FIG. C.2. Left: Scanning electron microscope image of a uniform array of holes with diameters of a few hundred nanometres in silicon. (Photograph courtesy of M.B.H. Breese, National University of Singapore). Right: Confocal microscope image of lattice of nitrogen-vacancy centres created by ion implantation of diamond. A few nitrogen-15 ions were irradiated into each irradiation spot. (Photograph courtesy of T. Ohshima, Japan Atomic Energy Commission.)

Beyond fundamental and applied research, particle accelerators are very important tools for industrial applications. The development of accelerator technologies capable of delivering highly stable and collimated ion beam currents, ranging from a few μA to 100 mA, and incident ion energies, ranging from 100 eV to ~10 MeV, have provided a broad and capable technology for the fabrication of integrated circuits for logic, memory and analogue operations, as well as an increasingly varied array of optical sensors and imaging devices. Ion implantation is nowadays broadly used in the semiconductor industry to create and modify electronic and photonic materials [C.4]. Today, scientists estimate that more than 17 000 accelerators are in operation worldwide, in research institutions, hospitals and industry [C.5].

C.2. Research Reactors

Research reactors are primarily used as a neutron source for research and various applications, with the most frequent applications shown in Table C.1. Their power can range from zero (e.g. critical or subcritical assemblies) up to approximately 200 MW(th), which is still low relative to 3000 MW(th) for a typical NPP. There is much greater design diversity for research reactors than power reactors, and they also have different operating modes, which may be steady or pulsed.

TABLE C.1. COMMON APPLICATIONS OF RESEARCH REACTORS AROUND THE WORLD [C.6]

Type of application [a]	Number of research reactors involved [b]	Member States hosting utilized facilities
Teaching/training	178	55
Neutron activation analysis	129	53
Radioisotope production	100	44
Material/fuel irradiation	85	30
Neutron radiography	74	41
Neutron scattering	53	35
Transmutation (silicon doping)	31	20

TABLE C.1. COMMON APPLICATIONS OF RESEARCH REACTORS AROUND THE WORLD [C.6] (cont.)

Type of application [a]	Number of research reactors involved [b]	Member States hosting utilized facilities
Geochronology	26	22
Transmutation (gemstones)	22	13
Neutron therapy, mainly R&D	19	13
Other[c]	141	38

[a] The recent Agency publication Applications of Research Reactors [C.7] describes these applications in more detail.

[b] Out of 284 research reactors considered (247 operational, 19 temporarily shut down, 6 under construction and 12 planned; 31 December 2014).

[c] Other applications include calibration and testing of instrumentation and dosimetry, shielding experiments, reactor physics experiments, nuclear data measurements, and public relations tours and seminars.

According to the IAEA's Research Reactor Database, 747 research reactors have so far been built and, as of 31 December 2014, 247 of them were operating [C.6]. The Russian Federation has the highest number of operational research reactors (including critical facilities) with 49, followed by the USA (41), China (15) and France (12). Many developing countries also have research reactors (e.g. 8 facilities are operating in Africa). Worldwide, 57 research reactors operate at power levels higher than 5 MW and thus offer high neutron fluxes supporting high capacity applications.

The majority of the operating research reactors remain heavily underutilized, and are on average over 45 years old. Therefore, many of them require continuous attention for ageing management, modernization and refurbishment. Interest in strategic utilization and business planning continues to grow to improve utilization and yield additional revenue. In the past two years, 37 research reactor facilities have prepared and submitted strategic plans to the IAEA for review. The IAEA organized a follow-up workshop in October 2014 to disseminate the lessons learned and share good practices among its Member States as a result of this review process. International collaboration continues to promote and enhance the utilization of research reactors for education and training. One example is the Internet Reactor Laboratory project in Latin America and Europe, which aims to connect universities with operating research reactors dedicated to education and training.

Several countries are at different stages of 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 (Fig. C.3), France, Jordan, the Republic of Korea, the Russian Federation and Saudi Arabia. Several Member States have formal plans to build new research reactors, including Belgium, Brazil, India, the Netherlands, the USA and Viet Nam. Others, such as Azerbaijan, Bangladesh, Belarus, Bolivia, Kuwait, Mongolia, Nigeria, South Africa, the Sudan, Thailand, Tunisia and the United Republic of Tanzania, are considering building new research reactors.[7]

The number of national operational research reactors is expected to continue to decrease as older reactors are decommissioned and replaced by research reactors that are shared by several countries. Greater international cooperation will be required to ensure broad access to these facilities and their efficient use. In this context, research reactor regional networks and coalitions, facilitated by the IAEA[8], help foster international cooperation and enable research reactors to

FIG. C.3. Argentina's Nuclear Regulatory Authority has granted a construction licence for the RA-10 research reactor, which will be used to increase the country's production of radioisotopes for materials/fuels testing, doping of silicon, as well as R&D. (Image: National Atomic Energy Commission.)

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[7] The IAEA publication Specific Considerations and Milestones for a Research Reactor Project is aimed at helping Member States in this area.

[8] The Agency has assembled several different research reactor coalitions in the Baltic, the Caribbean, Central Africa, Central Asia, Eastern Europe, the Mediterranean region and in the Commonwealth of Independent States.

expand their stakeholder and user communities. In addition, a new scheme of collaboration was launched by the IAEA in 2014, namely the IAEA designated International Centre based on Research Reactor.

The USA's Global Threat Reduction Initiative (GTRI) continued throughout 2014 to carry out its mission to minimize the use of HEU in the civilian nuclear sector. By the end of 2014, 92 of 200 research reactors within the scope of implementation of the GTRI had been converted to LEU fuel or confirmed as shutdown, including one molybdenum-99 production facility that had used HEU. Major successes include the Russian Federation's preparation and loading of the LEU fuel core into the ARGUS reactor, which reached first criticality in July, and the discharge of liquid HEU fuel from the shutdown FOTON reactor in Uzbekistan. During 2014, China, Ghana and the IAEA signed an agreement to support the conversion of the GHARR-1 research reactor through the transfer of LEU fuel. The technical prerequisites were clarified and an action plan was adopted to implement the conversion and HEU return.

HEU minimization activities include the return of HEU research reactor fuel to the country of origin where it was enriched. By the end of 2014, the take-back programme for US origin HEU fuel had completed 76% of its objectives with the removal of nearly 1300 kg of fresh and spent HEU research reactor fuel. The Russian origin take-back programme is 86% complete, with the removal of 2160 kg of fresh and spent HEU research reactor fuel. Following the conversion of Poland's Maria research reactor to LEU fuel, 53 kg of spent HEU fuel was shipped back to the Russian Federation in September. In Kazakhstan, 10.2 kg of fresh HEU and 37.3 kg of spent HEU fuel from the WWR-K facility in Alatau (which is in the process of HEU to LEU conversion) was returned to the Russian Federation (Fig. C.4).

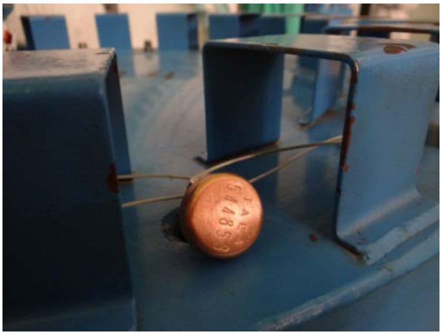

FIG. C.4. IAEA safeguards seal on a TK-S16 transport container (left). Transport containers are prepared for the flight to the Russian Federation from Almaty, Kazakhstan (right).

Conversion to LEU and repatriation of HEU fuel are often followed by significant infrastructure upgrades. For example, the IAEA's Peaceful Uses Initiative is funding a comprehensive modernization programme at Mexico's TRIGA Mark III research reactor.

Advanced, very high density uranium–molybdenum fuels that are currently under development are required for the conversion of high flux, high performance research reactors. Although substantial progress in this field has been made, further efforts and testing, particularly for irradiation and post-irradiation examination programmes, as well as in the area of manufacturing techniques, are necessary to achieve commercial availability of qualified LEU fuels. In November, the Russian Federation's TVEL Fuel Company signed a contract to begin supplying LEU fuel to the High Flux Reactor in the Netherlands.

While there were no major shortages of molybdenum-99 in 2014, operational challenges at processing facilities and older research reactors continue. Owing to changes in demand, efficiencies gained, and some diversification in supply, the minor shortages did not result in a crisis on the scale witnessed between 2007 and 2010. The conversion of medical isotope production processes from HEU to LEU continues, with the Australian Nuclear Science and Technology Organisation (ANSTO) and NTP Radioisotopes, South Africa, continuing to be the major suppliers of non-HEU molybdenum99. In 2014, ANSTO broke ground for its new molybdenum-99 production facility, which is expected to increase production from 1000 to 3000 6-day curies of LEU based molybdenum99 per week. NTP Radioisotopes is continuing to convert its processes to the exclusive use of LEU. Two other major medical isotope producers, the Institute for Radioelements in Belgium and Mallinckrodt in the Netherlands, have initiated efforts to support the conversion of their commercial scale production processes from HEU to LEU.

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D. NUCLEAR TECHNIQUES TO IMPROVE ANIMAL HEALTH

Nuclear and nuclear related technologies are playing an important role in animal health, particularly in relation to disease diagnosis and characterization of pathogenic organisms. This review focuses on how and where nuclear technologies, both non-isotopic and isotopic methods, have made an impact in the past, and where it might be expected they could have an impact in the future.

D.1. Use of Irradiated Vaccines to Protect Livestock from Transboundary Animal Diseases

Vaccination is a critical tool to protect animals and humans from life-threatening diseases. Most vaccines rely on some form of pathogen attenuation or inactivation, where chemical or physical methods are used, whilst in both cases maintaining immunogenicity and, therefore, inducing protective immune responses. In general, attenuated live vaccines induce better and stronger protection than inactivated vaccines, as the killing process destroys some of the proteins that are important for the induction of good immunity.

An alternative to chemical or physical treatment for vaccine development is irradiation. It can be applied in a way that progressively destroys or debilitates the pathogen's genomic nucleic acid, whilst conserving its antigen properties and thereby triggering a better host immune response. Recent advances in irradiated vaccine development have demonstrated that it is possible to obtain metabolically active but non-replicating microorganisms that can stimulate the immune response in a similar way to an exposure to a live pathogen. A purified culture of a live pathogen, cooled or frozen, is placed in the irradiator and exposed according to a programme stipulating a specific time interval and energy level (Fig. D.1). For example, for a trypanosomosis organism, an irradiation level of ~100 Gy is used. The irradiated pathogen solution is then mixed with cryoprotectants to stabilize the solution during the freezedrying process before it is used as a vaccine candidate [D.1].

Cobalt-60 sources are commonly used to irradiate pathogens; however, X rays and electron beams can also be used. The dose varies according to the pathogen. Studies have shown that the third stage larvae of the parasites *Haemonchus contortus* and *Strongylus colubriformis* attenuated by exposure to 600 and 700 Gy respectively protected sheep from these parasite infections [D.2]. The lungworm *Dictyocaulus viviparous* requires a lower dose (400 Gy), otherwise the trematode cannot migrate to the lungs to start inducing protective immunity [D.3]. Bacteria such as Brucella can be attenuated with

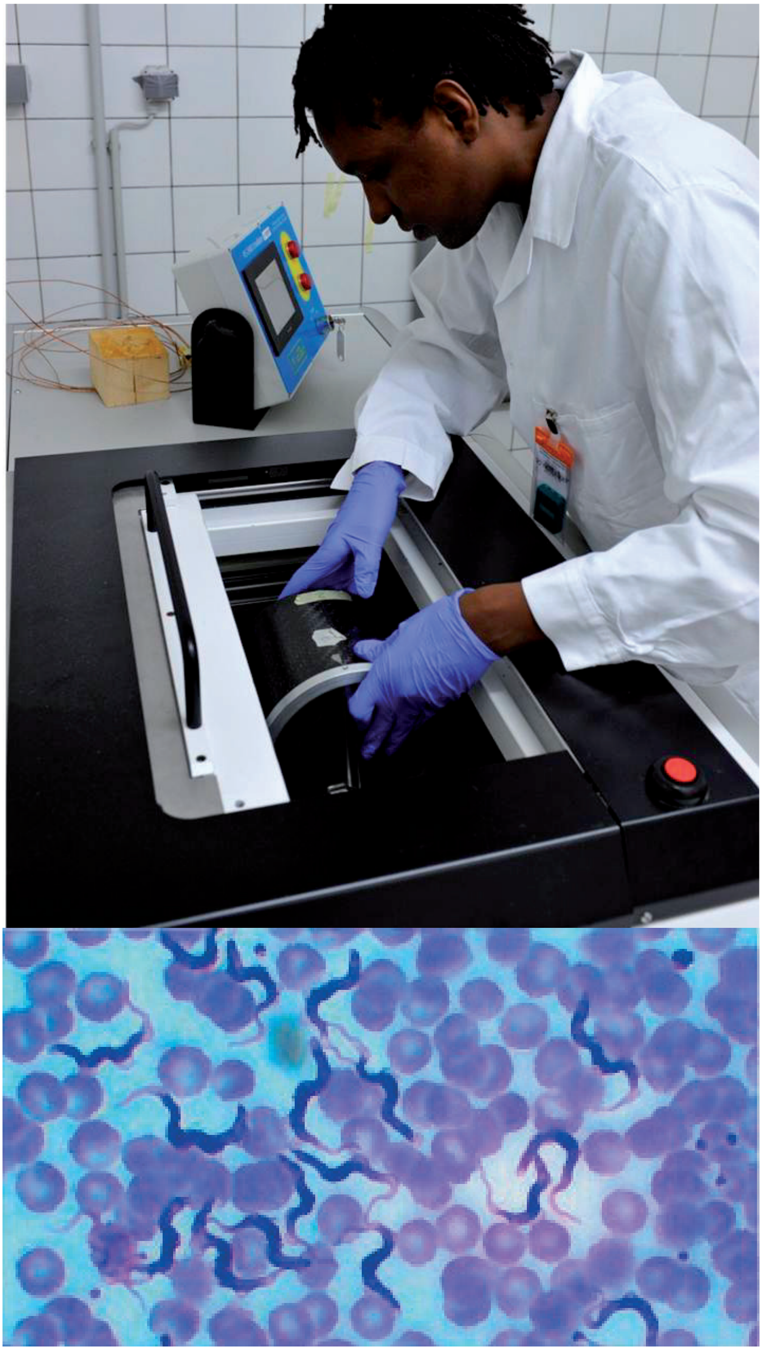

FIG. D.1. Irradiation of in vitro trypanosome cultures (T. evansi) using an X ray source.

3000 Gy [D.4], Pasteurella with 6000 Gy [D.5] and *Bacillus anthracis* with 20 000 Gy [D.6]. Viruses require higher doses to affect their proteins and structure. The foot and mouth disease (FMD) virus is inactivated with 40 000 Gy [D.7], and bluetongue virus requires 60 000 to 100 000 Gy [D.8].

D.2. Nuclear Techniques for the Early and Rapid Diagnosis of Transboundary Animal and Zoonotic Diseases

Early, rapid diagnosis is critical for the control of transboundary diseases. Diagnostic tests are carried out on host samples (blood, serum, tissues and secretions) to detect pathogens or antibodies. Radiolabels have been instrumental in the improvement of disease diagnostic tests for the identification of pathogens or their antigens or antibodies (proteins elicited from exposure to a pathogen's antigens).

Previously, to detect disease in a sample, immunoassays used radiolabelled DNA or proteins of a particular pathogen as an antigen to provoke an immune response. These assays were performed mainly in qualified laboratories, but as enzymes and fluorescent dyes replaced isotope labelling, the tests were extended widely to the field. The use of enzymes and fluorescent dyes, although practical, never achieved the high level of specificity and sensitivity observed with radioisotopes. Where high levels of sensitivity and specificity are needed (e.g. to diagnose H5N1 avian influenza, FMD, Rift Valley fever or African swine fever), isotope labelling is a consistently reliable early and rapid diagnostic technique. The IAEA pioneered the development of quality assured and affordable assays to diagnose a number of infectious and parasitic diseases such as FMD, brucellosis, rinderpest and trypanosomosis. Trained personnel of numerous national disease diagnostic laboratories have implemented these assays in their home countries for the control of animal and zoonotic diseases (Fig. D.2).

A dramatic improvement in the diagnosis of infectious diseases occurred with the advent of nucleic acid amplification platform technologies (e.g. polymerase chain reaction). This made possible the early, rapid and confirmatory diagnoses of especially highly infectious pathogens or those that were difficult to isolate and grow in vitro. Nucleic acid detection started with the labelling of DNA/RNA with tracers such as sulphur-35, sulphur-35 methionine, phosphorus-35 and phosphorus-32. The main advantage is that extremely low levels of infection can be detected in the animal (e.g. DNA probes prepared from, *Ostertagia ostertagi*, *Cooperia oncophora*, [D.9] *Haemonchus placei* and *Oesophagostomum radiatum* were able to detect as few as 25 eggs in faecal samples from infected goats, sheep and cattle). This enabled the detection of a pathogen before the onset of disease.

FIG. D.2. Training on nuclear and molecular techniques for the control of animal and zoonotic diseases at the Joint FAO/IAEA Laboratories in Seibersdorf.

Nuclear derived techniques are playing a role in combating the current Ebola virus disease (EVD) outbreaks in Western Africa. The IAEA has initiated a project with three components aimed at supporting capacity building, prevention and early detection, and improving existing diagnostic tools. The first component consists of technical, equipment and reagent/consumable support to already established diagnostic teams in the field. The second component will target the zoonotic nature of EVD and monitor the animal (wildlife) to human interface in order to prevent or enable early detection of virus intrusions from natural animal carriers into the human population. The third component will target the official diagnostic laboratory networks operating under the veterinary and/or public health authorities. This will entail adaptive implementation or improvement of existing diagnostic tools to ensure quality assured early, rapid, sensitive and specific detection and tracing of EVD. This comprehensive package will help countries at risk to manage the ongoing EVD outbreaks, as well as to respond rapidly in case of any future EVD threats.

D.3. Nuclear Techniques for the Tracing and Monitoring of Transboundary Animal and Zoonotic Diseases

In a world where the movement of animals or their products is commonplace and in which changes in the environment due to climate change can potentially affect the spread of infectious diseases and their vectors, there is a critical need for technologies that enable the geographical origin of those diseases to be identified and, where necessary, provide information on the feeding habits and associated movements of their vectors. The SIA technique can be used to provide the means to understand the epidemiology of diseases. Stable isotopes are the naturally occurring forms of elements that do not undergo radioactive decay. There are over 250 in existence; however, only a few are involved in important biological and ecological processes. The isotopes are measured by mass spectrometry as isotopic differences relative to international standards and reported as ratios in delta (δ) units as parts per thousand. The value of SIA is based on the strong correlation between the levels of certain isotopes in the environment and the concentration of the same isotopes in animal tissues.

Hydrogen (δ^2H) and oxygen ($\delta^{18}O$) ratios in tissues of animals are used to study animal movements, since these ratios accurately reflect the animals' movements between different feeding habitats such as lakes, rivers, oceans and groundwater. Using stable isotopes to characterize a population involves examining the isotopic signatures of a few individuals that are representative of the entire population (Fig. D.3). Studies have been in progress for several years using stable isotopes to characterize and differentiate between animal populations (particularly birds) using $\delta^{13}C$ and $\delta^{15}N$ values in metabolically active tissues (blood and muscle), but at present the most effective tracers appear to be the hydrogen isotopes found in metabolically inert, seasonally grown tissues, such as feathers, beaks and claws. Feathers retain this information until they are replaced or have moulted, typically once per year. Conversely, claws are continuously growing and can theoretically provide a time integrated profile, depending on claw growth rates. Once the isotope profile of a particular bird population is known, any individuals from the population can provide information on the global migration of that species.

FIG. D.3. SIA (stable isotope analysis) is helping to determine the role of migratory birds in the dissemination of the avian influenza virus across continents.

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E. ADVANCEMENTS IN MEDICAL RADIATION DOSIMETRY

The use of ionizing radiation for medical purposes is well established. In radiation therapy, radiation is used to destroy malignant cells, making the radiation dose to the target volume the tool for treating patients. In medical imaging, radiation is used to produce a diagnostic image, with any dose delivered to the patient being just an unavoidable side effect. Although the basic principles and objectives of radiation therapy and diagnosis differ significantly, the knowledge of the radiation dose is in all cases of primary importance, either to verify that the treatment is carried out as prescribed or to estimate the risk associated with a patient being exposed to radiation during a medical imaging procedure.

E.1. Medical Imaging

E.1.1. Patient dosimetry in diagnostic radiology

The United Nations Scientific Committee on the Effects of Atomic Radiation has highlighted that medical exposure, particularly diagnostic radiology, is by far the largest human-made source of exposure to ionizing radiation, and that it continues to grow at a substantial rate [E.1]. The main reasons are the large number of X ray examinations performed, and the sometimes inappropriate use of complex, high dose techniques, such as computed tomography (CT).

Therefore, there is a need to monitor and control patient doses and to optimize the design and performance of X ray imaging systems. Patient dosimetry is the primary responsibility of the medical physicist specializing in diagnostic radiology and has been introduced into national legislation and regulations in many countries. Dosimetric measurements in diagnostic radiology are required for the establishment and use of guidance levels, for the assessment of equipment performance, and for comparative risk assessment.

Diagnostic X ray imaging is used in a diverse range of examination types, from simple projection radiography to advanced cross-sectional dynamic imaging. This has resulted in the development of a wide range of dosimetric quantities, measuring instruments and techniques, all of which present challenges to those working in the clinical environment.

In general, quantities used for dosimetry in diagnostic radiology can be divided into two broad categories:

(i) Application specific quantities, which are practical dosimetric quantities that can be directly measured and which may be tailored to specific situations or modalities. These quantities include incident air kerma, the air kerma–area product (mainly used for projection imaging) and the CT air kerma indices, for cross-sectional imaging (Fig. E.1).
(ii) Risk related quantities, which can be used to estimate radiation detriment or risk and are thus measures of absorbed dose. These quantities cannot be directly measured and are only derived through calculation from application specific quantities or computation through appropriate models.

Depending on the diagnostic modality and the type of dose measurement required, several types of dosimeter can be used, provided they have suitable sensitivity and energy response, but typically, ionization chambers of a few cubic centimetres in volume, or solid state detectors specifically designed for such measurements, are used. Other types of dosimeters frequently used in diagnostic radiology are films (either radiographic or radiochromic), thermoluminescent dosimeters and optically stimulated luminescence dosimeters.

The IAEA's work in this area has focused on the harmonization and standardization of patient standards for implementation in hospitals.

E.1.2. Internal dosimetry in nuclear medicine

Clinical applications of nuclear medicine include both diagnostic imaging and therapeutic treatments. Internal dosimetry in diagnostic nuclear medicine aims to measure the doses received by healthy organs, while in molecular radiotherapy it is used as a tool for establishing doses absorbed by the tumours and organs at risk.

FIG. E.1. Measurement of dose in CT in a standard polymethyl methacrylate body phantom, and in air.

Nuclear medicine diagnostic procedures allow functional imaging of normal and diseased tissue, the most common applications being the localization of malignant tissue and the assessment of myocardial perfusion. The amount of radioactivity administered to the patients is typically low and the diagnostic benefit of the imaging procedure greatly outweighs the risks. Nevertheless, tissue doses and their stochastic risks should be quantified for each patient and placed in the context of the cumulative values received by the patient over multiple imaging sessions or received as a result of other diagnostic imaging procedures (e.g. CT or fluoroscopy). Therefore, the amount of administered activity has to be optimized in order to maximize the diagnostic quality of the image, while minimizing patient risk. This is particularly important for paediatric patients, because of their enhanced organ radiosensitivities and the increased number of years over which any stochastic effects may manifest themselves.

In therapeutic nuclear medicine, radioactive agents are employed to treat various forms of cancer and other diseases. While in external beam radiotherapy the radiation dose to the target organ or tissue is prescribed and a treatment planning system is used to accurately plan the prescribed dose to each patient, in therapeutic nuclear medicine, such a personalized process is not applied. Instead, the administered activity to the patient is determined by the type of tumour being treated (e.g. 150 millicuries of iodine-131 for thyroid cancer). Often, no pre-treatment assessment is carried out and the doses received by target tissues and organs at risk are not optimized, leading, in the majority of cases, to patients being undertreated. The reasons for this include a lack of training, resources and standardized methods based on the delivery of a dose prescription to the tumour, and a shortage of data on tumour–dose response relationships. This is slowly changing and the scientific community is becoming increasingly aware that patient specific dosimetry is essential for optimal efficacy and patient safety.

In internal dosimetry, tissue absorbed doses (the amount of energy from ionizing radiation absorbed per unit mass of the tissue) are generally assessed according to the medical internal radiation dose method. This method requires the calculation of the cumulated activity (total number of disintegrations that have occurred over time) for each source organ where the radiopharmaceutical is taken up. This method also requires the assignment of S values (absorbed dose to target tissues per decay in each source tissue), based upon internationally accepted reference anatomical phantoms (Fig. E.2).

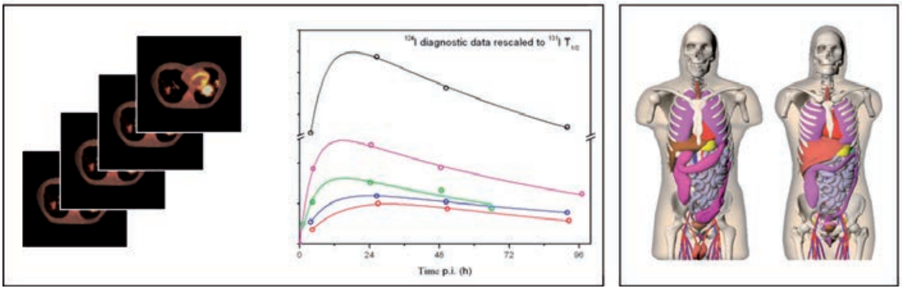

FIG. E.2. Left: Series of images and derived time–activity curves for different source organs. Right: an example of mathematical phantoms used for S value calculations.

E.2. Radiation Therapy

A key requirement in the radiotherapy process is that there should be consistent reference dosimetry standards and procedures. In external beam dosimetry, dose to water standards have been almost universally adopted, through codes of practice such as Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water [E.2], in megavoltage X ray dosimetry for medical linear accelerators and cobalt-60 machines. However, there has been a recent increase in radiotherapy techniques that use small fields, such as various forms of stereotactic radiotherapy, stereotactic body radiotherapy, stereotactic radiosurgery and intensity modulated radiation therapy. These developments have increased the uncertainty of clinical dosimetry and called into question the appropriateness of applying in this area existing reference dosimetry protocols for conventional radiotherapy such as Technical Reports Series No. 398 [E.2]. In some cases, unfortunate accidents have occurred because methods and procedures have been used that are adequate for large fields, but inadequate for small fields. A code of practice for the dosimetry of static small photon fields is therefore being developed that will standardize the dosimetry of small fields.

Since the publication of Technical Reports Series No. 398 [E.2], many different particle beam delivery systems have been developed for radiotherapy, such as proton and heavy ion beams. These systems make it possible to improve the treatment of the tumour, without increasing damage to normal tissue. Codes of practice to support accurate dosimetry for these beams are being developed.

Calibrated, well-type chambers are the preferred dosimeter for the calibration of radioactive sources used for brachytherapy. However, there is a lack of internationally harmonized quality assurance/quality control guidelines for all sources used in brachytherapy and also in the associated recommended dosimetry instrumentation. Many clinics do not have calibrated equipment, internal redundancy procedures or convenient access to independent intercomparisons. As a result, a range of methodologies are used to determine the source strength. Efforts are being made to establish absorbed dose to water standards in order to achieve harmonization with external beam radiotherapy dosimetry codes of practice, including Technical Reports Series No. 398 [E.2].

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F. DEVELOPMENTS IN RADIOPHARMACEUTICALS

Progress in nuclear medicine relies on the development of efficient production methods for novel radionuclides. Impressive progress has been made in the development of radioisotope production technologies as demonstrated by the recent introduction of high energy and high current cyclotrons. This has allowed broader access to a number of new radionuclides, including gallium-68, copper-64, zirconium-89 and zinc-63, and has facilitated the development of accelerator based technologies for the commercial production of technetium-99m, which still remains the most widely used diagnostic radionuclide. The availability of new radioisotopes for medical applications may solve as yet unforeseen clinical problems. These advancements are dramatically changing the nuclear medicine landscape.

F.1. Advances in Production Technologies

Recent technological improvements in cyclotron technology are increasing the yields of key medical radionuclides, thus enabling their widespread clinical use. A major problem for medical applications of radiopharmaceuticals is to ensure a constant supply of key radioisotopes, which are the essential components of these diagnostic and therapeutic agents. As described below, new radiopharmaceuticals, obtained from a number of different radionuclides, are demonstrating highly promising properties for cancer diagnosis and treatment. However, the availability of these important radioisotopes is currently limited by their low production yields when produced using low energy and low current medical cyclotrons. Another challenge is the expected shutdown of nuclear reactors that have provided the worldwide supply of technetium-99m, which still plays a fundamental role in diagnostic nuclear imaging.

Cyclotron technology as applied to the production of medical radionuclides is now mature. Available proton energies of commercial cyclotrons currently range from 6 MeV to 70 MeV. Important advancements have been achieved with the constant increase of proton current that can be as high as 750−800 μA. High current flows overcome limitations in radionuclide production yields arising from low values of cross-sections for proton interaction. The availability of high current flows has stimulated important advancements in the technology for assembling solid targets able to efficiently dissipate the significant heat generated by these high currents. With these new technological achievements, it will be possible to produce some crucial radionuclides such as gallium-68, strontium-82 and technetium-99m in larger amounts and ensure their broader supply.

Global interruptions in the supply of molybdenum-99 (^{99}Mo), the parent radionuclide yielding the most widely used diagnostic radionuclide technetium-99m (^{99m}Tc), have accelerated the search for alternative sources of ^{99m}Tc. Alternatives include the use of linear accelerators and cyclotrons. Unlike the typical fission process of producing ^{99}Mo in a reactor using uranium targets, these technologies use molybdenum-100 (^{100}Mo) targets. A linear accelerator can be used to produce ^{99}Mo through the transmutation of enriched ^{100}Mo whereas the cyclotrons can be used to produce ^{99m}Tc directly by irradiating ^{100}Mo. A significant environmental and economic advantage of the technologies is that little waste is generated and projects have demonstrated efficiency in the 90% range with respect to ^{100}Mo recycling.

F.2. Novel Radionuclides and Radiopharmaceuticals

This section describes promising applications of newly discovered radiopharmaceuticals for both cancer diagnosis and therapy.

F.2.1. Gallium-68

In the field of positron emission tomography (PET), the importance of the radionuclide gallium-68 is continuously growing, particularly because of its ready availability through the germanium-68/gallium-68 generator. Gallium-68 is a pure positron emitter with a half-life of 73 minutes. In the past few years, a few somatostatin–peptide-based gallium-68 radiopharmaceuticals have been described in various monographs and have reached the status of recognized diagnostic agents for neuroendocrine tumours (NETs). Although this category of NET tracers still remains the only example of clinically accepted gallium-68 radiopharmaceuticals, there are numerous studies on the development of new agents for the diagnosis of other types of cancer. For example, a tracer has recently been described for imaging prostate tumours. The structure of this radiopharmaceutical is particularly simple. It is composed of a gallium-68 ion bound to a ligand bearing an inhibitor of the prostate specific membrane antigen (PSMA). This new PSMA targeting ligand was first investigated in combination with the radionuclide ^{99m}Tc and then further modified for preparing the corresponding gallium-68 derivative. Highly promising results have been obtained in a number of clinical trials with prostate cancer patients that are currently under way to fully demonstrate the diagnostic efficacy and sensitivity of this novel radiopharmaceutical. Available data strongly suggest that this new agent can detect prostate cancer relapses and metastases with significantly improved contrast when compared to fluorine-18-labelled choline, which is the conventional tracer commonly employed for imaging prostate tumours.

F.2.2. Copper-64

It is difficult to find new and effective diagnostic and therapeutic radiopharmaceuticals because of the complexity of the human biological system. Sometimes, however, unexpected findings occur, as in the case of the discovery that copper-64, in its simplest chemical form of copper(II) ions, is quantitatively accumulated by a variety of tumours, including prostate, melanoma, breast and cerebral cancers. Simple copper-64 ions can selectively target cancer cells without having to be linked to some biological vector.

Copper is an essential trace element that is necessary for the activity of a number of metalloenzymes. A number of tissue abnormalities and disease states in humans have been associated with either reduced or elevated levels of copper. Serum copper levels are elevated in cancer patients and correlate with the severity of the disease and response to therapies. Experimental evidence demonstrates that levels of bioavailable copper modulate tumour growth, although the molecular and cellular mechanisms by which copper ions modulate tumorigenesis in different cancer types remain unclear [F.1]. As a result of this essential role played by copper ions in the replication of cancerous cells, copper ions are accumulated inside the cell nucleus in close contact with the genetic material whereas, in normal cells, they remain stored in the cytoplasm. Since copper-64 decays through the simultaneous emission of β^+ and β^- particles with a half-life of 12.7 hours, it could be used as both a diagnostic and therapeutic radionuclide by exploiting its enhanced uptake by tumours. This dual use of the same radionuclide is a perfect example of the 'theranostic' concept[9], where therapeutic and diagnostic capabilities are combined into a single agent. Copper-64 can be easily produced using a conventional low energy medical cyclotron by irradiation with protons of a solid nickel-64 target. Recently, sterile aqueous solutions of copper-64 chloride salt have been approved as pharmaceutical precursors for the preparation of copper-64 radiopharmaceuticals. After the discovery of the unexpected selective targeting of cancer cells by copper-64 ions, these solutions are currently employed in various clinical trials aimed at evaluating both the diagnostic and therapeutic efficacy of copper-64 chloride for the treatment of different tumour types and particularly of melanoma, breast cancer and prostate carcinoma.

F.2.3. Zirconium-89

The use of radiolabelled antibodies as imaging probes to visualize tumours has always been a promising area in molecular imaging. In particular, PET with radiolabelled monoclonal antibodies (MAbs) is an attractive method for non-invasive tumour detection and treatment planning. Among the commonly used PET radionuclides, only a few are suitable for antibody labelling since imaging with antibodies requires that the radioisotope be attached to the MAb with good in vivo stability and its decay half-life should match the pharmacokinetics of the MAb. Currently, the radioisotope zirconium-89 is attracting much interest for antibody labelling since its physical half-life of 3.3 days is compatible with

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[9] A theranostic approach uses a diagnostic test to determine whether a patient may benefit from a specific therapeutic drug. Current excitement about theranostics originates from this revolutionary approach that may allow improved therapy selection on the basis of specific molecular features of disease, thus opening up new ways to objectively monitor therapy response. Imagers use methods that permit non-invasive visualization of physiology utilizing various modalities to characterize anatomic, biochemical and functional pathology. Nuclear medicine has practiced this form of combined diagnostic–therapeutic procedure for decades, exploiting the original use of radioiodine as arguably the earliest imaging based molecular theranostic agent. Imaging with the γ emitter iodine-123 and combined therapy with the β emitter iodine-131 has been the cornerstone of adjuvant therapy for differentiated thyroid cancers. There are numerous examples of paired molecular imaging–therapy techniques with radiopharmaceuticals that are selective for biochemical processes, such as cellular proliferation, steroid synthesis, growth factor receptor expression, catecholamine production, hypoxia-induced gene expression or apoptosis. In summary, the theranostic approach may provide an attractive paradigm for the future development of medical applications of radionuclides because of its intrinsic ability to exploit in vivo imaging that may yield meaningful pharmacokinetic and biodistribution information on the presence of suitable molecular targets for a more fundamental and effective therapy.

the time needed to achieve optimal tumour to background ratios for intact MAbs (typically a few days).

Zirconium-89 decays by positron emission and electron capture and the maximum energy for its positron emission results in PET images with good spatial resolution. Zirconium-89 can be produced in a medical cyclotron by bombardment of an inexpensive natural yttrium foil mounted on an aluminium/copper disc with a proton beam of 14–14.5 MeV energy.

To date, a wide variety of MAbs have been labelled with zirconium-89 and several of these have entered clinical investigation with promising results. These include trastuzumab (Herceptin) for imaging human epidermal growth factor receptors type 2, cetuximab for imaging epidermal growth factor receptors, bevacizumab for targeting vascular endothelial growth factor receptors and MAb J591 for monitoring PSMA receptors [F.2].

F.2.4. Alpha emitters

Recently, a pharmaceutical grade radium-223 dichloride solution (the drug Xofigo) was the first α emitting radiopharmaceutical to be approved for clinical use in the treatment of metastatic bone disease. Other α emitting radionuclides that are medically relevant and currently available for potential therapeutic application are astatine-211, bismuth-212, bismuth-213, actinium225, radium-223, lead-212, thorium-227 and terbium-149. Production technologies for these radionuclides range from nuclear reactors to cyclotrons and generator systems. There is a continuous effort to develop simpler and more efficient methods for producing α emitting radionuclides to make them widely available for investigational purposes. Another key aspect of the research on α therapy is the need to establish efficient chemical procedures for tethering the α radionuclide to a selected vector molecule. In fact, unlike lighter β particles, the massive character of α particles might have a greater impact on the stability of the resulting radioconjugate in solution, thus indicating that robust chemical approaches should be applied to achieve a satisfactory stabilization.

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G. ISOTOPES IN CLIMATE AND HYDROLOGICAL STUDIES: RECENT DEVELOPMENTS AND TRENDS

Water is a critical resource for sustainable development as its availability influences almost all sectors of social and economic activity. Securing access to safe drinking water, as well as adequate freshwater supply for sanitation, food production and energy generation is a continuing challenge for many countries, affecting the lives of billions of people. However, variations in the availability of fresh water are poorly understood and estimates of the total amount of available water in rivers, lakes and aquifers, as well as its storage and flow, vary. Climate change is expected to affect local and regional water cycles, requiring a better assessment of the available resources at different temporal and spatial scales. Reliable hydrological information is required for the adoption of sound policies to successfully manage water supplies in the light of a changing climate and reduced per capita availability of water.

The assessment and management of water resources require multidisciplinary, science based approaches, building on physical and social sciences that must be strongly supported by scientific data on the occurrence, distribution and movement of surface water and groundwater. Naturally occurring stable and radioactive isotopes of water and their dissolved constituents are powerful tools for tracing water cycle processes, including the origin and pathways of rainfall and snowmelt flowing into aquifers, lakes and rivers and the hydraulic interactions between these bodies of water. The isotopic fingerprints in water help to rapidly and cost effectively assess and manage water resources and demonstrate how water plays a role in and is affected by climate change.

G.1. The Water Cycle and Climate Change

A sound understanding and characterization of the atmospheric processes leading to climate change, together with a better quantification of water fluxes within the water cycle, are critical for the assessment of the availability of water. Stable isotopes in precipitation and surface water have been used for decades to decipher and quantify hydrological processes, study atmospheric circulation, validate climate models, and simulate present and past climatic conditions. Initially, the need to understand the migration of atmospheric fallout from nuclear testing in the 1950s and 1960s provided unprecedented insights for hydrological processes in the atmosphere. The Global Network of Isotopes in Precipitation (GNIP) was launched in 1961 and is operated by the IAEA in cooperation with the World Meteorological Organization, providing key isotope data for studies in atmospheric sciences, hydrology and other fields.

In order to understand the impact of climate change on future precipitation, it is necessary to understand its impact in the geological past. Isotopic relationships in modern precipitation, derived from the GNIP data, are the most important means of characterizing water cycle changes in palaeoclimates by using environmental archives such as polar and continental ice, tree rings, lake and marine sediments, and groundwater. Recent analytical developments allow easier access to stable isotope data in precipitation and river water, resulting in the establishment of numerous new monitoring sites, facilitating the expansion of isotope monitoring at finer temporal and spatial scales. Simpler, cheaper and low maintenance laser based instruments are contributing enormously to the expansion of applications based on stable isotopes, with many hydrologists becoming self-reliant in conducting their own isotope measurements.

Many scientific disciplines dealing with environmental issues incorporate stable isotopes as tracers of sources, processes and interactions in nature. To further enhance the ability to detect and monitor climate effects on the water cycle, a global network is being developed by the IAEA to monitor isotopes in river water. Together, isotope data in modern and past precipitation offer a means to improve the global climate models used for predicting the effects of future climate change.

G.2. Assessment and Management of Water Resources

More precise estimates of available water resources in rivers and lakes and the extent of interconnections with groundwater at catchment scale are required for integrated water resources management. Even though groundwater presently contributes more than half of all fresh water used globally, there is limited reliable information on groundwater available in both shallow and deep aquifers worldwide. The use of isotopes to estimate the source and age of groundwater is critical, and in some cases unique, for the assessment of groundwater resources and their renewability. Tritium in groundwater has been used for many years as the primary hydrological tracer in the case of recently recharged groundwater, but current levels in these waters are often very low, making a quantitative interpretation difficult. However, when tritium measurements are combined with those of the product of its radioactive decay, the noble gas helium-3, this set of isotopes helps quantify modern recharge. This information is also essential for the protection of groundwater resources from pollution.

In view of water scarcity, which is a problem not only in arid and semi-arid regions, new sources of fresh water have to be explored in aquifers at greater depths. In many instances, groundwater recharged in the past under different climatic conditions is being extracted, but little is known about the amount and flow of these deep, possibly fossil, groundwaters with ages in the order of tens of thousands of years to more than a million years. In such aquifers, isotope dating by several age indicators, mainly long lived radionuclides and noble gas isotopes, such as carbon-14, helium-4 and krypton-81, is the only means by which these groundwater resources can be assessed. While carbon-14 has been used for many decades as an age indicator of groundwater, its use is limited by its half-life (about 5700 years) and the complex geochemistry of carbon in many aquifers. Noble gases, such as krypton-81, due to their chemically inert nature, offer advantages as age indicators, since these isotopes do not interact with the geological matrix of the aquifer. Recent analytical developments allow the precise determination of a few atoms of these rare isotopes in old groundwater, allowing the estimation of groundwater ages up to one million years.

H. UNDERSTANDING CHANGES IN THE MARINE ENVIRONMENT USING NUCLEAR TECHNIQUES

H.1. Nuclear Techniques to Study Global-Scale Changes

Nuclear techniques are being used to study carbon CO_2 in the marine environment. Increases in atmospheric CO_2 are progressively affecting the marine environment, in particular the acidity of seawater. Radionuclides offer powerful tools to understand the changing carbon cycle and how this affects organisms. They can also be used to reconstruct palaeo-changes of seawater chemistry in order to understand present changes and how these may affect oceans in the future.

The Earth's oceans absorb about 25% of all anthropogenic CO_2 emissions and therefore play an important role in restricting rising atmospheric CO_2 concentrations. Subsequently, biological activity incorporates a fraction of this CO_2 into organic carbon and calcium carbonate particles, which eventually sink in a process known as the biological pump. The naturally occurring radionuclide thorium-234 can be used to quantify this rate of biological removal of CO_2 from the upper ocean. Understanding the magnitude and rate of this process is essential for completing our picture of the carbon cycle and will help us to find ways of reducing the ocean's acidity.

When CO_2 is absorbed by the ocean it acidifies the water, which in turn affects marine organisms. Radioisotopes are used to investigate changes to marine organisms' processes such as calcification (calcium-45) (Fig. H.1), biomineralization (strontium-85), metabolism (zinc-65) or bioaccumulation of trace elements (e.g. cobalt-57, cobalt-60, manganese-54 or selenium-75) in response to this increasing acidity. Palaeo-reconstruction of seawater pH is also being studied, using the boron-10 and boron-11 isotopic composition of long lived massive corals, which in turn can be used in forward looking climate models to estimate future impacts on corals.

Carbon dioxide and methane (CH_4) are potent greenhouse gases that are cycled through the atmosphere via a variety of sources and sinks. These sources and sinks can be traced using stable isotope markers, or 'fingerprints', contained within the carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) stable isotopic signatures of the CO_2 and CH_4 molecules. Recent years have seen the development of optical isotope analysers that are capable of the highly precise and accurate measurements needed to study the small but dynamic atmospheric changes in CO_2 and CH_4. This can only be achieved using fit for purpose reference gas mixtures of CO_2

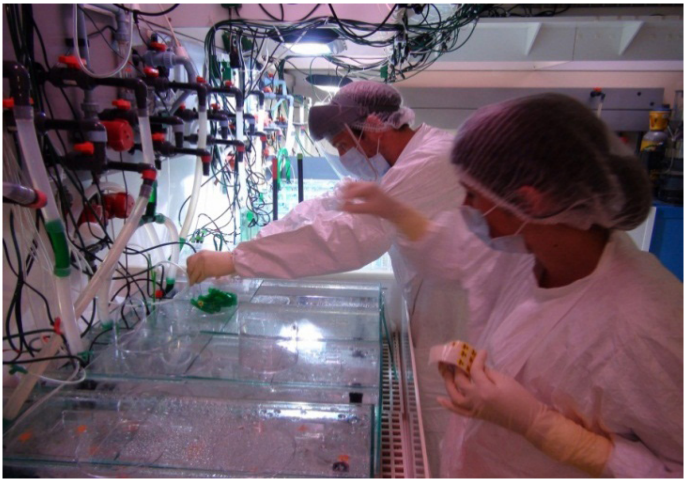

FIG. H.1. Experimental work using radiotracers (calcium-45) to understand the impact of ocean acidification on marine organisms.

or CH_4 in air calibrated using international stable isotope reference materials provided by the IAEA.

H.2. Nuclear Techniques to Study Local Environmental Changes

There is a wide range of nuclear and stable isotope techniques available for the study of environmental changes and pollution processes. These techniques are key tools for reconstructing past pollution events, as well as for tracking pollution trends and the effectiveness of pollution control measures. They are also used to study land based pollution sources of nutrients that cause coastal eutrophication, to distinguish between anthropogenic and natural concentrations of pollutants, to identify pollution sources for forensic pollution studies and to identify biotoxins related to harmful algal blooms (HABs) in seafood for the protection of human health.

Persistent pollutants (e.g. HMs and organic contaminants) are often deposited in marine sediments in estuaries, coastal areas and lagoons, which are often close to urban areas, fisheries and places of recreation. Lead-210 can be used to measure the rate of sedimentation and hence the rates at which pollutants accumulate. With a half-life of 22.3 years, a geochronology dating back 100150 years can be constructed and linked to contamination events such as nuclear accidents or testing, or environment related events such as eutrophication or HABs.

Human related eutrophication in coastal zones, which is mainly caused by runoff from urban effluents and agricultural land, is a widespread problem in a great number of estuaries and coastal areas. Degradation symptoms include elevated concentrations of phytoplankton, reduced water transparency, depletion of dissolved oxygen and, in some cases, the occurrence of HABs. Stable nitrogen isotope ($\delta^{15}N$) ratios are used as indicators of anthropogenic eutrophication in aquatic ecosystems, since elevated $\delta^{15}N$ values in sedimentary organic matter and biota indicate anthropogenic nitrogen discharges to coastal waters. Furthermore, since eutrophication leads to raised $\delta^{13}C$ values due to increased marine phytoplankton production, the compound specific carbon isotope analysis of lipid biomarkers reflects the strength of eutrophication events in coastal waters.

Identifying sources of contaminants in the coastal marine environment is important not only to understand environmental change processes, but also to plan for measures to control pollution. Therefore, nuclear techniques to trace pollution sources are valuable tools to protect the environment and promote the sustainable delivery of ecosystem services.

Oil pollution of coastal waters is a worldwide environmental problem, caused by operational, accidental or illegal petroleum hydrocarbon discharges. There is an increasing need for sensitive and reliable methods to monitor oil pollution and its impact, and to develop methods that identify the origin of oil pollution for regulatory purposes. The most developed methodology for characterizing oil spills is based on the chemical fingerprinting approach, where a series of petroleum constituents can be profiled by gas chromatography–mass spectrometry. However, the analysis of stable carbon isotope ($\delta^{13}C$) ratios in petroleum hydrocarbons can also be used as an additional forensic tool to fine-tune the fingerprinting of oil slicks with the aim of tracing oil sources in the marine environment.

Lead is a non-essential toxic element that can also be traced using isotopic ratios to reveal different sources of contamination to the marine environment (Fig. H.2). Lead ore deposits typically have distinct isotopic compositions, which reflect age, source and formation processes. Variations in stable and radiogenic lead isotope ratios, and especially the ratios relative to the only natural lead isotope (lead-204), can be used to trace sources and pathways of lead pollution.

FIG. H.2. High resolution inductively coupled plasma mass spectrometer used to analyse stable lead isotopes in environmental samples.

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