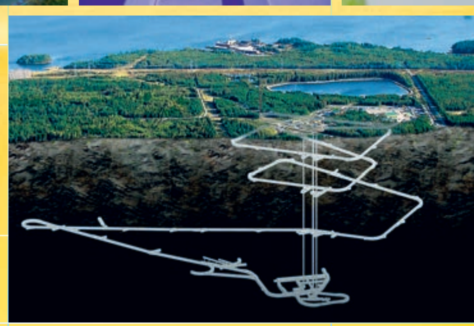
NUCLEAR TECHNOLOGY REVIEW

2016



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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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EDITORIAL NOTE

CONTENTS

EXECUTIVE SUMMARY

With 441 reactors operating at the end of 2015, nuclear energy had a global generating capacity of 382.9 GW(e). Seven reactors were permanently shut down, ten were connected to the grid, the highest number since 1990, and construction started on eight. Near and long term growth prospects remained centred in Asia, particularly in China. Of the 68 reactors under construction, 45 were in Asia, as were 39 of the 45 reactors that were connected to the grid since 2005.

Thirty countries currently use nuclear power and about the same number are considering, planning or actively working to include it in their energy mix. Of the 30 operating countries, 13 are either constructing new plants or actively completing previously suspended construction projects, and 12 are planning to either construct new plants or complete suspended construction projects. The IAEA's 2015 projections for 2030 show nuclear capacity growth to be between 2 and 70%. The role nuclear power plays in reducing greenhouse gas emissions is getting wider recognition. Having already made a sizeable contribution to climate change mitigation by avoiding nearly 2 billion tonnes (t) of carbon dioxide every year, nuclear power can directly contribute to achieving the United Nations Sustainable Development Goals.

Safety improvements have continued to be made at nuclear power plants (NPPs) throughout the world. The IAEA published its report on the accident at the Fukushima Daiichi nuclear power plant. At a diplomatic conference, the Contracting Parties to the Convention on Nuclear Safety adopted the Vienna Declaration on Nuclear Safety, which included several principles for preventing accidents with radiological consequences and mitigating such consequences, should they occur.

Global annual enrichment capacity remained above the total demand, while other fuel cycle activities operated at relatively constant levels. The basic legal framework necessary for the establishment of the IAEA low enriched uranium bank has been concluded with the signature, in August 2015, of the Host State Agreement and the related technical agreements with Kazakhstan.

Spent fuel from nuclear reactors in storage amounted to around 266 000 t of heavy metal (HM) and is accumulating at a rate of around 7000 t HM/year. Spent fuel reprocessing from commercial reactors continued to be carried out at ten facilities in five Member States.

Considerable decommissioning work is expected in the years to come: 157 nuclear power reactors worldwide have been permanently shut down or are undergoing decommissioning. More than 56% of all the operating reactors are more than 30 years old and about 15% of them are more than 40 years old. Although some may continue to operate longer, many will be retired from service within the next two decades. In addition, more than 480 research reactors and critical assemblies, and several hundred other fuel cycle facilities have been decommissioned or are undergoing decommissioning. The first construction licence for a deep geological disposal facility for spent nuclear fuel was granted for the Onkalo facility in Finland. Disposal facilities for all other categories of radioactive waste are operational worldwide. Disposal options for disused sealed radioactive sources (DSRSs), including co-disposal with other waste at suitable facilities, recycling, repatriation or disposal in dedicated boreholes, are under serious consideration in several countries. Successful removal operations in 2015 brought many DSRSs under proper storage conditions.

Several Member States continued to research, develop or deploy advanced fission reactors. There is increased global interest in developing and deploying fast reactors. There is also growing interest in small and medium sized or modular reactors (SMRs) owing to the need for flexible power generation, enhancing safety performance through passive safety features, and offering better economic affordability. There are about 50 SMR designs and concepts, and three are under construction.

Using nuclear energy for non-electric applications, such as for seawater desalination, hydrogen production, district heating, tertiary oil recovery and other industrial applications, is of broad interest to several Member States. Efforts to provide energy from nuclear fusion, the grand engineering challenge of the twenty-first century, are under way with construction works progressing at the International Thermonuclear Experimental Reactor (ITER) site.

There is increasing demand for high power proton or ion beam accelerators in fields such as particle, nuclear and neutron based physics, and in the transmutation of long lived nuclear waste.

About half of the world's 246 research reactors and critical facilities in operation in 55 countries are more than 40 years old. Ageing management, sustainability of fuel supply, options related to spent fuel management and enhancement of research reactor utilization are the major challenges for the research reactor community.

Initiatives such as the Internet Reactor Laboratory, the IAEA-designated International Centre based on Research Reactor scheme, as well as regional networks and coalitions are aimed at fostering international cooperation in capacity building, including education and training. Eight countries are constructing new research reactors, while several others are planning or considering building new ones as key national facilities for the development of nuclear science and technology infrastructure and programmes, including nuclear power. High enriched uranium (HEU) minimization activities, including the return of HEU research reactor fuel to the country of origin, continued. The take-back programmes for HEU fuel of US and Russian origin have achieved commendable results over the years. With the addition of Uzbekistan, 28 countries[1] that had HEU are now HEU-free.

While there were no major supply shortages of the medical isotope molybdenum-99 during 2015, operational challenges at processing facilities and older research reactors continued. Because of changes in demand, efficiencies gained and diversification in supply, the minor unscheduled outages were well managed by the industry.

Nuclear techniques are widely used in industrial processes to investigate complex physical and chemical phenomena, including wear, mass transfer, corrosion and erosion. When surfaces are not easily accessible or are concealed by overlying structures, the nuclear technique of thin layer activation offers an effective way of measuring and monitoring wear and corrosion. Ultra thin layer activation allows a surface loss measurement sensitivity of a few nanometres to be achieved.

Novel radiation processed products such as radiation synthesized nanoscale materials in various shapes and sizes (nanoparticles, nanofibres, nanopores) are envisaged for use in the preparation of active packaging for food and wound dressing materials, as well as for use as drug delivery devices. ‘Active’, or ‘intelligent’, packaging with superior gas barrier properties that can prevent oxygen from entering and inert gases from leaving food packaging, thus extending the life of the product, is being developed. Films of this kind can be made by incorporating specific nanoparticles into the film, which could also contain enzymes, anti-bacterial agents and other components that help to control food degradation and spoilage.

In the printing and coating industry, the need for procedures that reduce pollution and avoid the migration of degraded by-products into consumer goods has been a leading factor in the emergence of low energy electron beam accelerators with energies of less than 300 keV for the coating industry. The use of radiation curable monomers and oligomers in coatings, inks and adhesives, which polymerize and cross-link, avoids the use of volatile organic compounds. The recent development of a new generation of highly compact and easy-to-operate electron beam emitters with an accelerating voltage range of 80 to 200 kV and treatment widths of up to 60 cm has the potential to further promote the use of this technology.

In health, there is considerable interest in the ongoing development of body composition assessment tools, as evidence suggests the individual components of body composition have a significant influence on chronic disease risk, disease progression and treatment response. Currently, three imaging modalities are used

[1] Plus Taiwan, China.

for body composition assessment: dual energy X ray absorptiometry, quantitative computed tomography and magnetic resonance imaging. Dual energy X ray absorptiometry involves simultaneous imaging at two distinct X ray energy levels and is a highly accurate and precise modality for measuring bone mineral density, bone mass, fat mass, lean soft tissue mass and fat percentage.

Recently, two and three dimensional (2-D and 3-D) whole body surface scanning systems have been proposed as novel platforms for body composition assessment, as their high accessibility, low cost and rich regional data make them compelling options for the assessment of regional body composition. Measurements acquired using 3-D surface scanners have been shown to be highly precise, while 2-D body shape measurements are acquired using a standard digital camera. It has recently been demonstrated that fat mass index and fat-free mass index can be derived from simple whole body silhouettes, which can be easily captured using conventional cameras, such as those found in mobile phones, making 2-D optical body composition measurements highly suited for a variety of field applications.

The integrated use of radiation, genetic and symbiont based methods to manage mosquito disease vectors may help reduce the associated disease burden. Pilot projects are showing that the sterile insect technique (SIT) can be integrated with other control tactics to effectively supress mosquito populations. Mass production is required for the SIT and other related population suppression interventions, but it is essential that only male mosquitoes are released, as female mosquitoes are the transmitters of disease. Sex separation to eliminate females from the production line is possible on a small scale using sexual dimorphism and spiking blood meals, but effective and robust genetic sexing strains for easy and safe elimination of female mosquitoes on a mass rearing scale are needed. Efforts are now ongoing to identify new morphological or conditional lethal markers for *Anopheles arabiensis*, *Aedes albopictus* and *Aedes aegypti* in order to develop effective genetic sexing strains.

Alongside conventional SIT using irradiation, *Wolbachia*, a genus of maternally inherited symbiotic bacteria that is abundant in insects, is being assessed as a complementary tool to suppress, through cytoplasmic incompatibility (incompatible insect technique (IIT)), major mosquito vector populations in some areas. In the absence of robust genetic sexing strains, the proposal to combine the SIT with *Wolbachia* based approaches seems to have great potential as an effective and biosecure approach to control mosquito vector populations, as it eliminates the risks associated with the release of fertile and disease transmitting females. A dynamic population suppression approach, which integrates the SIT and other compatible tactics in an area-wide insect pest management programme, may be the only way to sustainably manage mosquito populations and, potentially, to control the many diseases they transmit.

Soil degradation caused by inappropriate farm management practices leads to a loss of fertile soil and poor crop yields. The loss of arable land and the sedimentation and pollution of streams and lakes are also significant environmental, social and economic threats. Up to 1.4 billion people may be impacted by land degradation, while ecosystem service losses have been estimated at US $10.6 trillion per year.

Strategies that help in assessing soil erosion and quantifying the effectiveness of soil conservation have long been guided by the use of fallout radionuclides (FRN) such as caesium-137, originating from thermonuclear weapon tests of the past, and naturally occurring geogenic radioisotopes such as lead-210 and cosmogenic radioisotopes such as beryllium-7. A recently developed forensic stable isotope technique based on the compound specific stable isotope (CSSI) signatures of inherent soil organic biomarkers allows for the sources of sediments to be discriminated and apportioned. By linking the CSSI fingerprints on the origins of sediments to the FRN information on soil and sediment redistribution, an accurate and powerful approach for determining sediment origins is available to researchers for identifying areas that are prone to soil erosion. Use of these integrated isotopic approaches could allow farming communities to adopt specific and effective mitigation measures to minimize losses of soil fertility, crop productivity and deterioration of water quality.

A. POWER APPLICATIONS

A.1. Nuclear power today

As of 31 December 2015, there were 441 operational nuclear power reactors worldwide, with a total capacity of 382.9 GW(e)[2] (see Table A.1). This represents an increase of some 6.6 GW(e) in total capacity, compared with 2014.

Of the operational reactors, 81.6% are light water moderated and cooled, 11.1% are heavy water moderated and cooled, 3.4% are light water cooled and graphite moderated, and 3.2% are gas cooled reactors. Two are liquid metal cooled fast reactors.

On 10 September 2015, Sendai-1 became the first nuclear power reactor to resume full operation in Japan since the Fukushima Daiichi accident, followed by Sendai-2 on 15 October 2015. Japan's Nuclear Regulatory Authority approved the restart of Ikata-3 in May 2015, which was also approved by the Ehime Prefectural Assembly in October 2015.

Five reactor units in Japan (Genkai-1, Mihama-1 and 2, Shimane-2 and Tsuruga-1), the Grafenrheinfeld reactor in Germany and the Wylfa-1 reactor in the United Kingdom were declared as permanently shut down in 2015.

In 2015, ten new reactors were connected to the grid, the highest number since 1990. Eight of these reactors (Changjiang-1, Fangchenggang-1, Fangjiashan-2, Fuqing-2, Hongyanhe-3, Ningde-3, and Yangjiang-2 and -3) are in China, one (Shin-Wolsong-2) is in the Republic of Korea and one (Beloyarsk-4) is in the Russian Federation.

There were eight construction starts in 2015: Fangchenggang-3, Fuqing-5 and -6, Hongyanhe-5 and -6, and Tianwan-5 in China, K-2 in Pakistan, as well as Barakah-4 in the United Arab Emirates.

As of 31 December 2015, 68 reactors were under construction. Expansion as well as near and long term growth prospects remain centred in Asia, particularly in China. Of the total number of reactors under construction, 45 are in Asia, as are 39 of the 45 new reactors to have been connected to the grid since 2005 (Fig. A.1).

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[2] 1 GW(e), or gigawatt (electrical), equals one thousand million watts of electrical power.

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2015) [A.1]

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2015		Total operating experience through 2015	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Argentina	3	1 632	1	25	6.5	4.8	76	2
Armenia	1	375			2.6	34.5	41	8
Belarus			2	2 218				
Belgium	7	5 913			24.8	37.5	275	7
Brazil	2	1 884	1	1 245	13.9	2.8	49	3
Bulgaria	2	1 926			14.7	31.3	159	3
Canada	19	13 524			95.6	16.6	693	6
China	31	26 774	24	24 128	161.2	3.0	209	2
Czech Republic	6	3 930			25.3	32.5	146	10
Finland	4	2 752	1	1 600	22.3	33.7	147	4

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2015) [A.1] (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2015		Total operating experience through 2015	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
France	58	63 130	1	1 630	419.0	76.3	2 048	4
Germany	8	10 799			86.8	14.1	816	7
Hungary	4	1 889			15.0	52.7	122	2
India	21	5 308	6	3 907	34.6	3.5	439	6
Iran, Islamic Republic of	1	915			3.2	1.3	4	4
Japan	43	40 290	2	2 650	4.3	0.5	1 739	0
Korea, Republic of	24	21 733	4	5 420	157.2	31.7	474	0
Mexico	2	1 440			11.2	6.8	47	11
Netherlands	1	482			3.9	3.7	71	0

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2015) [A.1] (cont.)

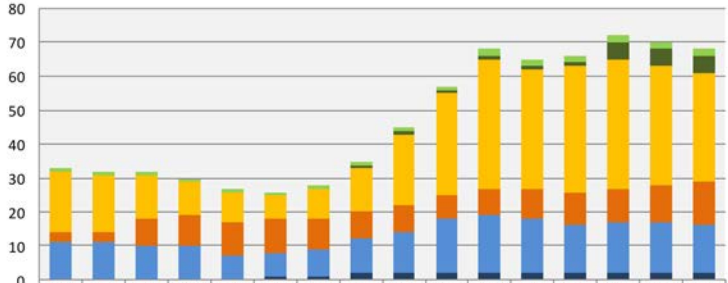
Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2015		Total operating experience through 2015	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Pakistan	3	690	3	1 644	4.3	4.4	64	8
Romania	2	1 300			10.7	17.3	27	11
Russian Federation	35	25 443	8	6 582	182.8	18.6	1 191	4
Slovakia	4	1 814	2	880	14.1	55.9	156	7
Slovenia	1	688			5.4	38.0	34	3
South Africa	2	1 860			11.0	4.7	62	3
Spain	7	7 121			54.8	20.3	315	1
Sweden	10	9 648			54.5	34.3	432	6
Switzerland	5	3 333			22.2	33.5	204	11
Ukraine	15	13 107	2	1 900	82.4	56.5	458	6

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2015) [A.1] (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2015		Total operating experience through 2015	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
United Arab Emirates			4	5 380				
United Kingdom	15	8 918			63.9	18.9	1 559	7
United States of America	99	99 185	5	5 633	798.0	19.5	4 111	4
Total [a, b]	441	382 855	68	67 442	2 441.3		16 536	7

[a] 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.

[b] 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).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
America - Latin	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
America - Northern	0	0	0	0	0	0	0	1	1	1	1	1	1	5	5	5
Asia - Far East	18	17	13	10	9	7	9	13	21	30	38	35	37	38	35	32
Asia - Middle East and South	3	3	8	9	10	10	9	8	8	7	8	9	10	10	11	13
Europe - Central and Eastern	11	11	10	10	7	7	8	10	12	16	17	16	14	15	15	14
Europe - Western	0	0	0	0	0	1	1	2	2	2	2	2	2	2	2	2

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

Of the 441 operational nuclear power reactors, 250 have been in service for 30 years or more (see Fig. A.2). When a reactor reaches the end of its design life, it undergoes a safety review and an ageing assessment of its essential structures, systems and components for validating or renewing its licence to operate for terms beyond the originally intended service period.

In the United Arab Emirates, the Emirates Nuclear Energy Corporation submitted an operating licence application on behalf of Nawah in March. Nawah will be the operating organization and the licence holder for Barakah-1. The Federal Authority for Nuclear Regulation is expected to issue an operating licence

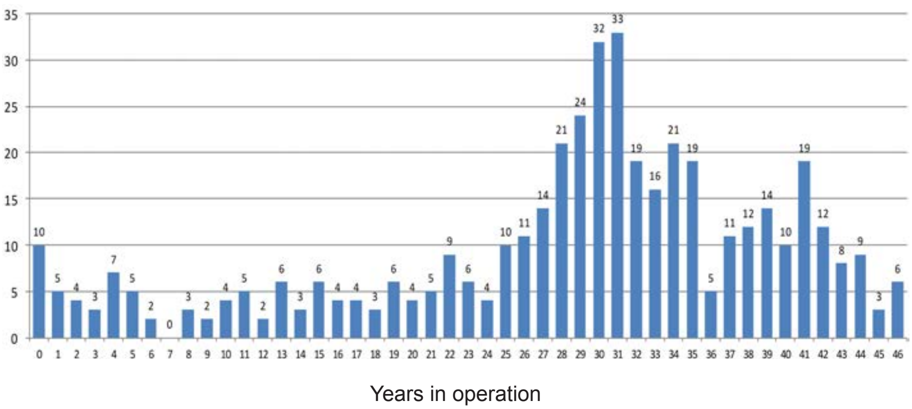


FIG. A.2. Distribution of operational power reactors by age, as of December 2015 [A.1].

in October 2016 to allow fuel loading and hot commissioning of Barakah-1. Barakah Units 2, 3 and 4, all under construction, are expected to be operational by 2018, 2019 and 2020, respectively. The IAEA conducted an Integrated Regulatory Review Service mission in February, an Emergency Preparedness Review mission in March, and an International Physical Protection Advisory Service mission in May 2015.

Construction continued on both units of Belarus' first NPP. Commissioning of Ostrovets-1 and -2 is planned for 2018 and 2020, respectively.

Turkey continues to develop its nuclear power programme infrastructure and has been finalizing a draft nuclear energy law that addresses safety, security and safeguards issues in a comprehensive way.

Bangladesh established the Rooppur Nuclear Power Plant Company as the future operator and started negotiations with the Russian Federation on credit agreement and a general engineering and construction contract. With plans to select a technology and a site for its first NPP by 2019, begin construction by 2022 and have its first unit operational by 2029, Poland developed tender documents and conducted negotiations on a government support mechanism planned to be adopted by 2018. Viet Nam implemented national projects on human resource development and public outreach, and continued to revise its Atomic Energy Law, which is expected to be submitted for approval in 2016.

Integrated Nuclear Infrastructure Review missions to Nigeria (June), Kenya (August) and Morocco (October) recognized the progress the countries had made in developing their nuclear infrastructure and made recommendations for further actions. In June 2015, Jordan signed contracts with the Russian Federation's Atomstroyexport to perform a water supply study and site supervisory activities. The Jordan Nuclear Power Company was established in October. Proposals for a grid study, electricity market research, and technical, legal and financial project development consulting services are under technical evaluation. Egypt signed an agreement with the State Atomic Energy Corporation "Rosatom" in November for the construction of four reactors.

In many countries considering nuclear power, the focus is on making an informed decision, on developing the comprehensive legal and regulatory infrastructure necessary to support a nuclear power programme, and on developing the required human resources.

Stakeholder involvement continues to be an important area of focus for countries at all stages of nuclear infrastructure development as it helps Member States address concerns early and explain their nuclear power programme's rationale, plans and progress. In 2015, the IAEA facilitated expert missions related to stakeholder involvement in Egypt, Indonesia, Kenya and Saudi Arabia as well as international meetings in Finland and Japan.

A.1.1. Expanding countries

The US Nuclear Regulatory Commission (NRC) has issued a 40 year operating licence to the Tennessee Valley Authority for Watts Bar Unit 2 to operate until October 2055. The Watts Bar site is the first to comply with the NRC's Fukushima related orders on accident mitigation strategies.

The construction of the Flamanville-3 European pressurized water reactor in France is ongoing with a scheduled deadline and connection to the grid by the end of 2018. Responding to a request by the French Nuclear Safety Authority, a series of tests are being performed to confirm that the metallurgical and mechanical characteristics of the pressure vessel head and bottom part comply with requirements.

Nucleoeléctrica Argentina and the China National Nuclear Corporation (CNNC) have concluded negotiations on the technical and commercial contracts for constructing Argentina's fourth reactor, the CANDU-type Atucha-3, which will take eight years to build. A framework agreement between the two organizations also foresees the construction of a Chinese designed Hualong One pressurized water reactor (PWR) as Argentina's fifth unit.

Fennovoima in Finland submitted a construction licence application to the Ministry of Employment and the Economy for its Hanhikivi project. The processing of the application is expected to take at least two years. Fennovoima aims to start building the plant based on the Russian designed 1200 MW(e) water cooled, water moderated power reactor (WWER) in 2018, with operation beginning in 2024.

A.1.2. Operating countries

Decisions on operating lifetimes mainly depend on the electricity market conditions and forecasts for business development, sometimes also coupled with social and political factors. In Sweden, four reactors will be closed earlier than originally planned because they are deemed unprofitable. Ringhals-2 will permanently shut down in 2019, with Ringhals-1 to follow in 2020, although both were initially scheduled to shut down around 2025. A final decision on when to shut down Oskarshamn-1 will be taken once a decommissioning schedule is ready. Oskarshamn-2, which has been out of service since June 2013 for an extensive modernization programme, will not be restarted.

Entergy in the USA will close its single unit Pilgrim NPP in Massachusetts no later than June 2019. It also intends to shut down its FitzPatrick NPP in New York in late 2016 or early 2017, citing declining economic viability as the reason.

The Republic of Korea's oldest operating reactor, Kori-1, operating since 1978 and refurbished in 2007, was approved to run until 2017. As the Korea

Hydro & Nuclear Power Company announced it will not apply for a relicensing process to take it to 2027, Kori-1will be the country's first nuclear power unit to enter the decommissioning phase when it shuts down in June 2017.

A.2. The projected growth of nuclear power

According to the IAEA's 2015 projections (Fig. A.3), in the high projection, the global nuclear power capacity is expected to grow from its current level of 381.7 GW(e) to 632 GW(e) by 2030 — an increase of about 70% in 15 years. In the low projection, the nuclear capacity in 2030 will be 385 GW(e), i.e. maintaining approximately its present level. These figures account for retirements — the actual new capacity added in the next 15 years will be about 150 GW(e) in the low case and 300 GW(e) in the high case. Extending these projections into the future results in nuclear capacity growing to 964 GW(e) in the high case by 2050, and net zero growth in the low case.

The high scenarios of the IAEA, the OECD International Energy Agency (IEA) [A.3] and the World Nuclear Association (WNA) [A.4] consistently show growth in the range of 600–700 GW(e) by 2030, while the low scenarios reflect larger growth uncertainties (Fig. A.4).

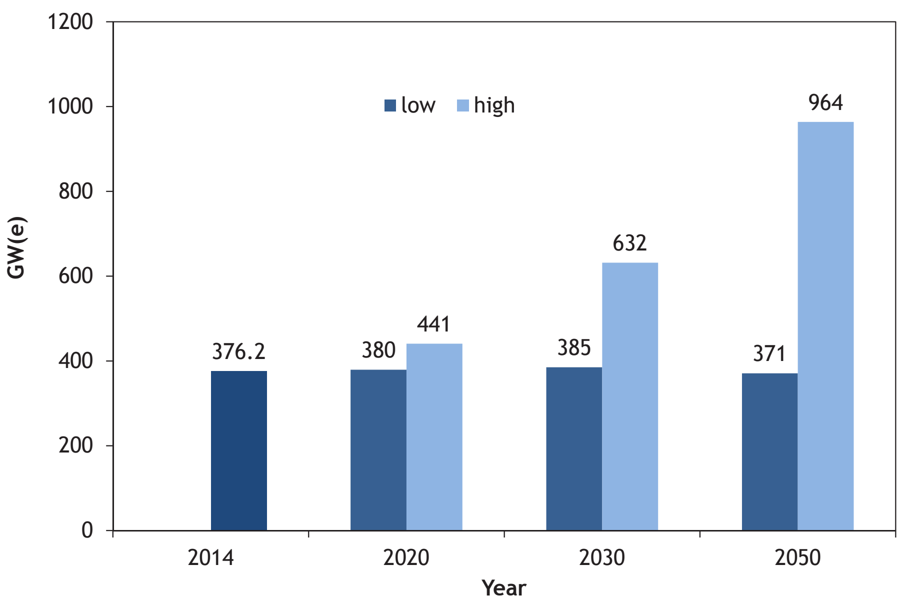


FIG. A.3. Projections for world nuclear capacity [A.2].

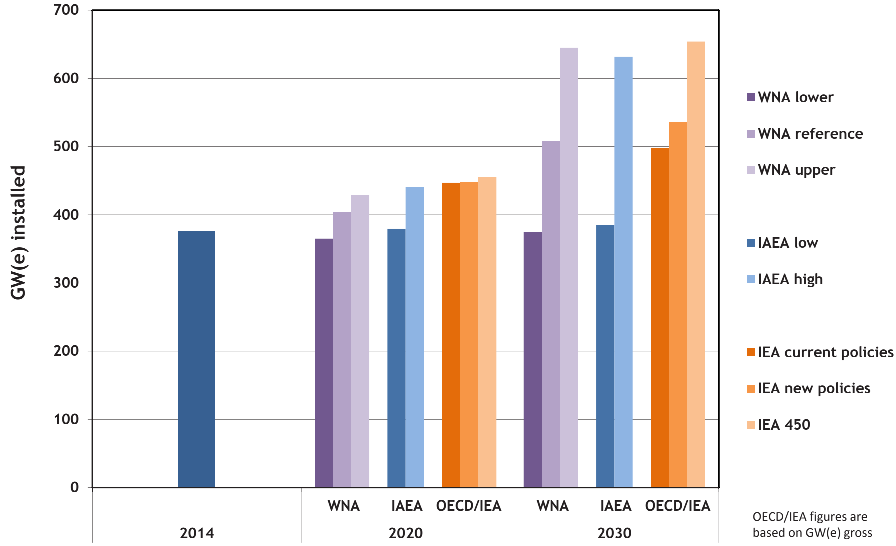


FIG. A.4. Comparison of the IAEA's latest projection with the OECD/IEA's [A.3] and the WNA's 2015 [A.4] scenarios.

Nuclear power has significantly contributed to climate change mitigation by avoiding nearly 2 billion tonnes of carbon dioxide per year. For nuclear power to help limit global warming to 2ºC by 2100, its capacity would need to match the high projection to avoid nearly 6.5 billion tonnes of greenhouse gas emissions by 2050. The 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) resulted in the Paris Agreement that neither identifies nor excludes any particular form of energy. This allows the countries to identify low carbon energy portfolios to offset carbon emissions. The Paris Agreement also supports sustainable development. Nuclear power can directly contribute to the United Nations Sustainable Development Goal 7, "Ensure access to affordable, reliable, sustainable and modern energy for all", and 13, "Take urgent action to combat climate change and its impacts" [A.5].

A.3. Fuel cycle

A.3.1. Front end

A.3.1.1. Uranium resources and production

Uranium spot prices remained depressed in 2015, oscillating between US $77/kg U and US $86/kg U, compared with a low of approximately US $60/kg U in mid-2014. Low prices considerably restricted the ability of companies to raise funds for exploration, feasibility studies, the launching of new construction projects and the expansion of existing ones.

The WNA estimates that uranium production was approximately 57 000 t U in 2015, more or less maintaining the levels of 2014. Uranium production is currently taking place in over 15 countries. A number of new projects are in various stages of development in some of the producing countries and in more than 25 potential newcomer countries, a few of which would be restarting uranium mining after a long hiatus.

Kazakhstan maintained its place as the world's leading uranium producer, almost entirely from its in situ leach mines. After rapidly increasing production between 2000 and 2012, recent increases have been modest to a 2015 production of 23 800 t U.

The second highest producer, Canada, continued to receive encouraging uranium exploration results from the Athabasca Basin, such as the Triple R uranium deposit, which could produce an estimated 38 770 t U over a 14 year mine life. Cigar Lake, the world's highest grade uranium mine, began commercial production in May and expects to achieve its full production capacity of 6900 t U/year by 2017.

The newly constructed Husab uranium mine in Namibia went through commissioning in 2015, with initial production planned in 2016. The full capacity could be 5770 t U/year, with a likely life of over 20 years. Namibia's Rössing and Langer Heinrich uranium mines continued operations in 2015.

In Australia, the Four Mile in situ leach uranium mine, which opened in 2014, ramped up production with a 1000 t U/year capacity. At the Ranger project, work on a possible underground mining extension to the previous two open cuts was suspended and will not proceed. Production during 2015 was less than 2500 t U, compared with 4000 to 6000 t U/year between 1997 and 2009.

The first phase of a refinery pilot plant to extract uranium and rare earth metals from the Kvanefjeld deposit in Greenland, Kingdom of Denmark, has met or exceeded its targets. Estimates announced in February include 228 100 t U and 11.13 million tonnes of total rare earth oxide. Unconventional uranium resources like the Kvanefjeld deposit significantly expand the resource base. Sea water is being investigated in the USA as another unconventional source of uranium. Thorium has been used in the past as nuclear fuel on a demonstration basis, but substantial work is still needed before it can be considered for commercial use. Worldwide resources of thorium are estimated to be about six to seven million tonnes.

A.3.1.2. Conversion and enrichment

Canada, China, France, the Russian Federation, the UK and the USA operate commercial scale plants for the conversion of triuranium octaoxide (U_3O_8) to uranium hexafluoride (UF_6). A dry fluoride volatility process is used in the USA, while all other converters use a wet process. The total world annual conversion capacity is around 60 000 t U as UF_6 per year. Total current demand for conversion services (assuming an enrichment tails assay of 0.25% uranium-235) is also in the range of 60 000–64 000t U/year.

Total global enrichment capacity is currently about 60 million separative work units (SWUs) per year, compared with a total demand of approximately 50 million SWUs per year. Commercial enrichment services are carried out by five companies: the China National Nuclear Corporation (China), AREVA (France), the State Atomic Energy Corporation “Rosatom” (Russian Federation), USEC (USA) and URENCO (both Europe and the USA).

Small conversion and enrichment facilities are in operation in Argentina, Brazil, India, the Islamic Republic of Iran, Japan and Pakistan.

The US NRC has approved a licence amendment allowing URENCO to expand its Eunice enrichment plant in New Mexico. The plan is to expand the capacity from the present 3.7 million SWUs to 10 million SWUs. The US Department of Energy, however, has announced a funding cut of some 60% to its uranium enrichment programme. The activities will now be limited to development of the new American Centrifuge uranium enrichment technology at Oak Ridge, Tennessee.

Deconversion of depleted UF_6 to uranium oxide or uranium tetrafluoride (UF_4) is undertaken for long term storage of depleted uranium in a more stable form. Current total world deconversion capacity remained at about 60 000 t UF_6 per year. 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 Electrochemical Plant (ECP) in Zelenogorsk, Russian Federation. International Isotopes is constructing a plant in New Mexico, USA. URENCO ChemPlants, UK, has delayed to 2017 the expected start date of the Capenhurst Tails Management Facility deconversion plant, currently under construction. When complete, the facility will process URENCO’s European inventory of depleted uranium.

The South Australian Government set up the nation's first Royal Commission on nuclear fuel, examining the potential for the expansion of fuel cycle activities.

A.3.2. Fuel fabrication

The current annual demand for light water reactor (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/year in the near future. Pressurized heavy water reactor (PHWR) requirements accounted for 3000 t U/year. There are now several competing suppliers for most fuel types. Total global fuel fabrication capacity remained at about 13 500 t U/year (enriched uranium) for LWR fuels, and about 4000 t U/year (natural uranium) for PHWR fuels. LWR fuel fabrication is currently done in Brazil, China, France, Germany, India, Japan, Kazakhstan, the Republic of Korea, the Russian Federation, Spain, Sweden, the UK and the USA. For natural uranium PHWR fuels, uranium is purified and converted to uranium dioxide (UO_2) in Argentina, Canada, China, India and Romania.

The US NRC has cleared the Perry NPP in Ohio to begin using Global Nuclear Fuel's GNF2 high performance boiling water reactor (BWR) fuel. This fuel promises higher energy output while cutting overall fuel cycle costs, reducing the total amount of uranium and the average enrichment in fuel reloads. The company also made its next generation GNF3 BWR fuel assembly available in 2015 (Fig. A.5), which provides improved fuel economics, increased performance and flexibility in operation. In April 2015, AREVA launched ATRIUM 11 fuel in two BWRs in the USA. The new design offers better operational flexibility, which is particularly valuable for plants that have implemented power uprates or optimized capacity factor operating strategies.

FIG. A.5. The next generation GNF3 fuel for BWRs. (Figure courtesy of Global Nuclear Fuel.)

Arizona Public Service Company, USA, has signed a contract with the Westinghouse Electric Company for the fabrication and delivery of its next generation fuel for three nuclear reactor units at Palo Verde, Arizona. The new fuel, known as CE16NGF, incorporates advanced cladding material and burnable absorbers, as well as advances in structural design that improve the fuel's efficiency and reliability while increasing its service life.

A group of US utilities in May 2015 submitted a formal expression of interest to the NRC for review of Lightbridge's novel metallic fuel design. The fuel is made from a zirconium–uranium alloy and uses a unique composition with multilobed and helically twisted rod geometry. The design offers improved heat transfer properties, enabling it to operate at a higher power density than uranium oxide fuels in use today. The fuel is expected to undergo irradiation testing in the Halden research reactor in Norway, starting in 2017.

A number of industrial and academic research laboratories are currently investigating various accident tolerant fuel concepts. New technology for manufacturing nuclear fuel components from silicon carbide has been developed in Japan by Toshiba and IBIDEN as a replacement for zircaloy cladding in LWRs. The fuel assembly cover will be tested in a research reactor in 2016 with the aim of commercializing it by 2025. In the UK, the National Nuclear Laboratory and the University of Manchester started a research project that includes work on advanced ceramic composite claddings, which could offer great potential to improve the temperature capabilities of nuclear fuel.

Qualification irradiation tests of fuel elements for the demonstration High Temperature Reactor–Pebble-Bed Module (HTR-PM), a high temperature gas cooled reactor being built at Shidaowan in China, have been completed in the Netherlands. In April, the Islamic Republic of Iran announced the opening of its first nuclear fuel production facility that will produce fuel similar to that used in the Bushehr NPP.

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

India and the Russian Federation manufacture MOX fuel for use in fast reactors. In the Russian Federation, the Mining and Chemical Complex finished preparations for release of a batch of standard fuel assemblies with MOX fuel for the BN-800 type Beloyarsk-4 reactor. Construction of new production lines was completed last year, with an annual production capacity of 20 fuel assemblies in

2015, and with an aim to produce 400 per year by 2017. The J-MOX facility in Japan, with a capacity of 130 t HM/year, is under construction and is expected to start commercial operation in 2019.

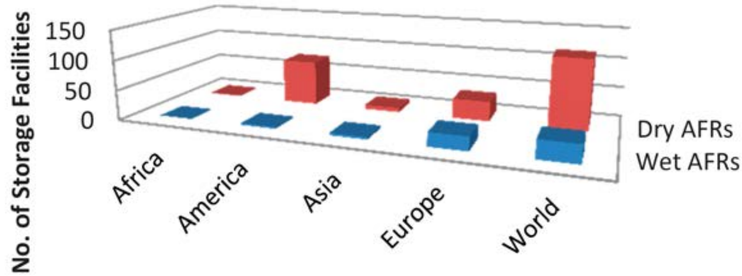
A.3.3. Assurance of supply

The completion of the legal framework in 2015 with Kazakhstan marked the transition of the IAEA Low Enriched Uranium (LEU) Bank project from assessment and feasibility studies to full scale implementation. Following approval by the Board of Governors, the Host State Agreement (HSA) and two subsidiary technical agreements were signed in Astana, Kazakhstan, on 27 August 2015. The first subsidiary technical agreement is the Facility Operator Agreement between the IAEA and the Ulba Metallurgical Plant, which will be the operator of the IAEA LEU bank. The second subsidiary technical agreement is with the Ministry of Energy on the specific arrangements to be implemented for the establishment of the IAEA LEU bank. Based on the agreement, a Joint Coordination Committee co-chaired by the IAEA and Kazakhstan was established, which agreed on a Plan of Specific Activities (PSA) within the foreseen 90 day period from the date of signing. Under the HSA, safety and security are ensured by Kazakhstan's nuclear regulatory system and the PSA provides a roadmap for demonstrating compliance with the applicable provisions of the IAEA's safety standards and security guidance documents as required by the HSA. Significant technical work continues in the areas of safety, specifically seismic safety, and security. A feasibility study was completed on storage facility options and a new building is under consideration. In June 2015, also following approval by the Board of Governors, a transit agreement was signed with the Russian Federation.

Other assurance of supply mechanisms in place are described in the Nuclear Technology Review 2012 [A.6].

A.3.4. Back end

By the end of 2015, spent fuel in storage amounted to around 266 000 t HM and is accumulating at a rate of around 7000 t HM/year. While most of the fuel is stored wet at the reactor site, there are 147 away-from-reactor spent fuel storage facilities (AFRs) in 27 countries (Fig. A.6). Canada and the USA have the largest spent fuel inventories in dry storage systems, each with over one third of their national inventory stored in such facilities. Germany has over 1000 metal dual purpose dry storage casks loaded and its whole spent fuel inventory is projected to be in dry storage by the end of 2022.



	Africa	America	Asia	Europe	World
Wet AFRs	0	3	4	23	30
Dry AFRs	1	75	7	33	116

FIG. A.6. Global distribution of away-from-reactor spent fuel storage facilities.

Currently, there are 12 countries either planning, constructing or in the process of commissioning dry storage facilities. The largest projects are in Japan, the Russian Federation, Spain and Ukraine. At Zheleznogorsk, Russian Federation, the largest dry storage capacity in the world has recently been completed with the addition of two new dry storage vault buildings (one for high-power channel-type reactor (RBMK) and one for WWER fuel) to the one completed in 2012. The new vaults are expected to receive spent fuel in 2016.

In the USA, the company 'Waste Control Specialists' has applied to the NRC for a licence to operate an independent spent fuel storage installation in Andrews, Texas. AREVA is to take a lead role in designing, constructing and operating the proposed facility. Holtec International and Eddy-Lea Energy Alliance have announced a memorandum of understanding for the design and construction of a centralized spent fuel storage facility to hold up to 75 000 t HM based on Holtec International's underground maximum security dry storage system. The facility would be located in south-eastern New Mexico if approved.

The global picture of spent fuel reprocessing from commercial reactors remained unchanged in 2015, with such reprocessing carried out at ten facilities in China, France, India, the Russian Federation and the UK. France and the UK have the largest deployed capacities and reprocess in the order of 1000 t HM/year. France and the Russian Federation offer reprocessing services for overseas customers. The Russian Federation's Mayak facility increased its annual processing capacity to 200 t HM/year and tested several technologies for reprocessing unconventional fuels such as beryllium–uranium fuel. India has three facilities for power reactor fuels and a 60 t HM/year pilot facility for thorium oxide fuel. China has a pilot reprocessing plant capable of reprocessing up to 50 t HM/year. In November, the CNNC and AREVA signed an agreement to build an 800 t HM/year spent fuel processing and recycling facility, expected to be in China's Gansu Province. Construction is expected to begin in 2020 and be completed by 2030. The site will also house a spent fuel storage facility with 3000 t HM capacity. Currently, there is no commercial reprocessing plant in Japan; however, the 800 t HM/year plant at Rokkasho is undergoing active commissioning and safety review, and it was expected to be operational by March 2016.

Based on the Mid-and-Long-Term Roadmap towards the Decommissioning of Tokyo Electric Power Company's (TEPCO's) Fukushima Daiichi Nuclear Power Station Units 1–4, of June 2013 [A.7], the removal of pooled fuel at Unit 3 of the Fukushima Daiichi NPP was scheduled for the first quarter of 2015. A number of challenges have prevented this target from being met, including difficulties related to the removal of the fuel handling machine console (removed in August 2015) and of related machinery, and the ability to decontaminate the Unit 3 operating floor to a target dose level of 1 mSv/h. In June 2015, the Roadmap was revised to reflect the situation on the ground. This has resulted in pooled fuel removal from Units 1 and 3 being rescheduled to 2020 and 2017, respectively.

A.3.5. Decommissioning, environmental remediation and radioactive waste management

A.3.5.1. Decommissioning of nuclear facilities

In addition to the 441 operational nuclear power reactors across the world, a further 157 have been shut down or are undergoing decommissioning, including 17 that have been fully decommissioned [A.1].

There are more than 320 fuel cycle facilities in operation, about 170 that have been shut down or are undergoing decommissioning and 125 that have been fully decommissioned. There are also 246 operational research reactors and over 180 that have been shut down or are undergoing decommissioning (Fig. A.7). More than 300 research reactors and critical assemblies have been fully decommissioned.

A significant level of decommissioning experience has been gained since the turn of the century, with the greatest progress achieved mainly in countries with long running nuclear power programmes, particularly in Belgium, France, Germany, the Russian Federation, Spain, the UK and the USA. Examples of programmes with substantial progress in decommissioning in 2015 include the segmentation of a reactor pressure vessel at the José Cabrera NPP in Spain, the commencement of second stage decommissioning at the Bohunice V1 NPP in

FIG. A.7. Decommissioning works at Sellafield, UK. (Photographs courtesy of Nuclear Decommissioning Authority/Sellafield Ltd.)

Slovakia and the completion in the Russian Federation of the large scale federal target programme, entitled Nuclear and Radiation Safety in 2008 and for the period up to 2015, which includes notable decommissioning and environmental remediation activities.

Progress in the UK continues towards the decommissioning of the ten first generation Magnox NPPs. The cessation of operations at Wylfa NPP (Anglesey, Wales) in December 2015 marked the completion of the Magnox generating era, which started with the grid connection of the world's first industrial scale NPP at Calder Hall (Cumbria, England) in August 1956. Wylfa started operations in 1971 and now enters the defuelling phase prior to decommissioning. Decommissioning is also continuing at Dounreay's two alkali metal cooled fast reactors and its Materials Test Reactor, as well as at Winfrith's two remaining research reactors.

Projects are also proceeding in Bulgaria, Lithuania and Slovakia, where NPPs were shut down before the end of their design lives and financial support is provided through the European Bank for Reconstruction and Development.

A.3.5.2. Management of disused sealed radioactive sources

Disposal options for DSRSs, including co-disposal with other waste at suitable facilities, an increasing number of recycling and repatriation options, or disposal in dedicated boreholes, are under serious consideration in several countries, including Ghana, Malaysia and the Philippines. 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. Through the IAEA, Canada has pledged funds to support programmes in Ghana and the Philippines to implement borehole disposal, and actions for this project have been initiated.

Several successful operations were conducted in 2015 to remove DSRSs from user premises and bring them under control in proper storage conditions. Three disused Category 1 and 2 sources were removed from Honduras and one Category 1 source was removed from Morocco. The repatriation of one French manufactured Category 1 DSRS was completed in Lebanon. The repatriation of a total of four more French manufactured Category 1 DSRSs was initiated in Cameroon, Lebanon and Tunisia, with the repatriations scheduled for 2016.

Significant progress was made to link the South African Nuclear Energy Corporation mobile hot cell to the design for borehole disposal, with the intent of minimizing the handling of sources and eliminating unnecessary transport. In addition, a mobile tool kit has been designed to facilitate conditioning operations of Category 3–5 DSRSs and to support preparation for borehole disposal. Operations involving the training of local and regional personnel and the conditioning of DSRSs were completed in Bangladesh, Chile, Madagascar, Paraguay, Peru, the Philippines and Sri Lanka.

The IAEA extended access to the International Catalogue of Sealed Radioactive Sources and Devices to many individuals in Member States, thereby facilitating the identification of DSRSs found in the field. Efforts to add more details on sources and devices were initiated in 2015, to further improve the usefulness of the catalogue.

A.3.5.3. Radioactive waste predisposal

In legacy facilities, notable progress was made at Sellafield, UK, particularly at the two historic open air ponds. At the Pile Fuel Storage Pond, the extraction of all canned fuel has removed the criticality risk associated with the pond and has reduced the radioactive inventory by 50%.

The First Generation Magnox Storage Pond (FGMSP) at Sellafield was constructed in the 1950s to store, cool and prepare spent Magnox nuclear fuel for reprocessing. It ceased operation in 1992 and now contains some 1400 m^3 of radioactive sludge, along with other inventory. In March 2015, a significant milestone was reached with the successful first transfer of radioactive sludge from the FGMSP to a newly commissioned store.

In the UK, the publication of a national strategy for solid low level waste (LLW) has led to the development of a significantly increased number of alternative treatment and disposal routes. As a result, in 2015, 85% of LLW generated by the nuclear industry was diverted away from the UK's Low

Level Waste Repository towards a range of treatment options including metal recycling, incineration and disposal of very low level waste (VLLW) in permitted landfill sites.

Georgia commenced the trial operation of a waste processing workshop to minimize waste and mitigate the risk posed by legacy waste. This uses a plasma cutting device and a customized grit blasting decontamination facility to remove surface bound radioactive contaminants from steel pipes arising from the decommissioning of a cryogenic station and the helium cooled low temperature nuclear research reactor, IRT-M.

Commercial incineration and metal melting operations in several countries, such as Sweden and the USA, continue to provide opportunities for cost effective, cross-border radioactive waste treatment services. For example, in specific cases, Canadian nuclear utilities and the Canadian Nuclear Laboratories may send certain low level operational and legacy radioactive waste to licensed service providers in the USA, with a much reduced volume of radioactive waste being returned.

The Novovoronezh NPP, in the Russian Federation, put into operation a plasma furnace with a capacity of 250 kg/h. The furnace will be used to process solid waste after the decommissioning of the NPP's first two units. In addition, a bituminization facility for liquid radioactive waste at the Kalinin NPP reached its design capacity, allowing volume reduction by a factor of ten and catering for all Russian NPPs.

The safe and secure storage of radioactive waste awaiting disposal is a key imperative for Member States with a waste inventory. In the Netherlands, the Central Organization for Radioactive Waste (COVRA) has received a licence to build a new interim storage building for depleted uranium and for the extension of the country's interim storage for high level waste, HABOG.

Lithuania has started cold trials of a solid radioactive waste management and storage facility at Ignalina NPP for the processing of legacy waste generated during NPP operations.

Belgium received the last of a total of 123 drums of high activity liquid waste immobilized in cement from the reprocessing of used fuel in the UK. This long lived, intermediate level waste will be stored in a purpose built storage facility at Dessel awaiting disposal.

At the Bhabha Atomic Research Centre in India, a recently developed new sorption process has separated large quantities of caesium-137 from high level waste to produce pencils of vitrified caesium-137 for use as blood irradiators.

Investigations into the February 2014 radiological event at the Waste Isolation Pilot Plant in New Mexico, USA, identified waste incompatibility (nitrates in contact with organic material) as being the most likely cause of the incident. This conclusion highlights the importance for all radioactive waste management programmes to establish comprehensive and robust characterization procedures to ensure compliance with the waste acceptance criteria.

The UK has inaugurated a national facility, MIDAS, at the University of Sheffield in partnership with the UK Department of Energy and Climate Change to support the management of radioactive waste from the nuclear fuel cycle. The facility gives technology developers access to state of the art equipment, including laboratories dedicated to high temperature processing, the study of long term waste form performance, and chemical and radiochemical analyses.

Progress continues to be made on the management of the large volumes of contaminated water and groundwater ingress at the Fukushima NPP site. Over one million cubic metres of water have been treated to remove one of the major contaminants, caesium, and provision is being made for strontium removal to augment the existing advanced liquid processing systems. Also, a groundwater bypass system designed to control ingress by groundwater to the reactor and turbine building has been successfully put into operation, with groundwater ingress having been reduced to about 25% (or 100 m^3) per day. Construction of the ice wall enclosing the areas around Units 1–4 continues.

A.3.5.4. Radioactive waste disposal

Disposal facilities for all categories of radioactive waste, except high level waste (HLW) and spent fuel, are operational worldwide. These include trench disposal for VLLW (e.g. in France, Spain, Sweden and the USA), or 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); and engineered facilities for low and intermediate level waste (LILW) sited in geological formations at a range of depths (e.g. in Finland, Germany, Hungary, Sweden and the USA).

Further disposal facilities for LILW are at different licensing stages, e.g. in Belgium (Dessel), Bulgaria (Radiana), Canada (Kincardine), Germany (Konrad), Lithuania (Stabatiškės), Romania (Saligny) and Slovenia (Vrbina, Krško).

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

In Finland, the waste management organization Posiva received a construction licence for the spent nuclear fuel geological disposal facility in Olkiluoto. Construction work under the licence can start towards the end of 2016 and the disposal facility is expected to be ready for operation in 2023.

In Sweden, presenting some preliminary outcomes from its ongoing regulatory review of the Swedish Nuclear Fuel and Waste Management Company SKB’s licence application for a spent nuclear fuel repository, the Radiation Safety

Authority stated that “SKB has demonstrated that there are prospects for meeting the Authority’s nuclear safety and radiation protection standards” [A.8].

The French National Radioactive Waste Management Agency is preparing a summary safety report for its Cigéo high level waste geological disposal project, in preparation for full licence application, planned for 2017.

Canada’s project to develop a deep geological repository (DGR) for Ontario Power Generation’s LILW at the Bruce nuclear site in Kincardine, Ontario, received a favourable recommendation in May by the Joint Review Panel, which was established in 2012 to assess the proposed facility. The official decision, expected in December 2015, was postponed to 2016 by the Minister of Environment and Climate Change, in the face of national and cross-border opposition from stakeholders voicing concern over the relative proximity to Lake Huron.

China foresees geological disposal needs deriving from the reprocessing of 140 000 t of spent fuel from a fleet of 48 reactors. An experimental tunnel is under construction at the Beishan site, as a precursor to construction of a first underground research facility to support the geological disposal programme.

In Germany, responsibilities for the disposal of radioactive waste have been reassigned, with the creation of two new federal organizations: the Federal Company for Nuclear Waste Management and the Federal Office for the Regulation of Nuclear Waste Management. To guide future developments for the national DGR, a national siting commission established in 2013 is expected to recommend site selection criteria in 2016, requirements for stakeholder participation, as well as whether alternatives to geological disposal could be considered.

The development of the near surface repository for LLW at the Talmesi site in the Islamic Republic of Iran is in progress. Having received the siting licence, construction of the central storage facility at the disposal site has been completed.

Japan has directed the Nuclear Waste Management Organization to revisit the DGR siting approach for HLW and has organized a suite of information events to raise general awareness.

The Wolsong underground silo type repository in the Republic of Korea was inaugurated in August (Fig. A.8). Construction of the second phase disposal facility has started and is planned to be finalized by 2019. Wolsong is planned to house 800 000 drums of LILW, and operate for 60 years.

The Russian Federation is progressing towards developing a DGR in Krasnoyarsk and has authorized the construction of an underground research facility to further investigate the Nizhnekansky formation.

The first two vaults of a new LLW disposal facility at Dounreay in northern Scotland, UK, have begun to receive waste. The vaults are designed to hold all solid LLW and demolition waste from the decommissioning of the site’s fast

FIG. A.8. Waste containers and first disposal activities at Wolsong. (Photographs courtesy of Korea Radioactive Waste Agency.)

reactors and reprocessing plants, thus minimizing waste transports from the remote location. The LLW disposal facility at the Drigg site has successfully renewed its environmental permit. 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 [A.9]. It outlines an approach to identifying potential sites for a geological disposal facility that is based on working with interested communities, beginning with a phase of dialogue and stakeholder engagement.

The US Department of Energy has issued a request for proposal for entities interested in providing a test site, a drilling contractor and a site management team to drill a 5000 m deep characterization borehole as part of its planned Deep Borehole Field Test. The concept involves drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5000 m, emplacing waste containers in the bottom 3000 m of the borehole and then sealing the borehole to the surface.

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 IAEA Action Plan on Nuclear Safety [A.10] remained at the core of the actions taken by Member States, the Secretariat and other relevant stakeholders to strengthen the 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 the International Experts Meeting on Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant in cooperation with the Nuclear Energy Agency (OECD/NEA), and the International Experts Meeting on Assessment and Prognosis in Response to a Nuclear or Radiological Emergency.

The IAEA published its report on the Fukushima Daiichi accident, which includes five detailed technical volumes [A.11]. The report was the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States, with and without nuclear power programmes, and several international bodies.

Following the decision of the Contracting Parties to the Convention on Nuclear Safety during their sixth review meeting, the Director General convened a diplomatic conference in February to consider a proposal by Switzerland to amend the Convention. The diplomatic conference unanimously adopted the Vienna Declaration on Nuclear Safety [A.12], which included principles to guide the Contracting Parties in implementing one of the objectives of the Convention, which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur.

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.9 shows the number of unplanned manual and automatic scrams or shutdowns per 7000 hours (approximately one year) of operation per unit. Scrams are only one indicator of safety performance, but this approach is commonly used as an indication of success in improving plant safety by reducing the number of undesirable and unplanned thermal hydraulic and reactivity transients requiring reactor scrams.

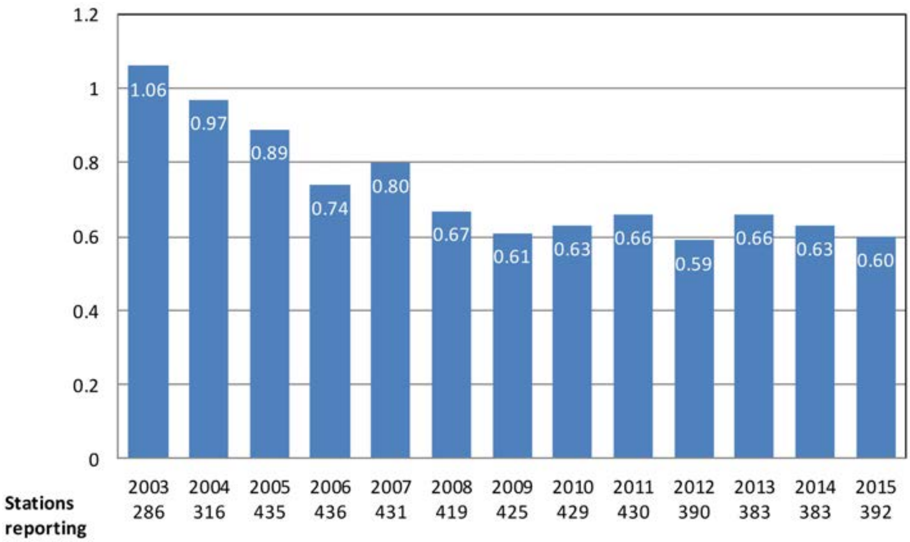


FIG. A.9. Mean rate of scrams: the number of automatic and manual scrams that occur per 7000 hours of operation per unit [A.1].

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B. ADVANCED FISSION AND FUSION

B.1. Advanced fission

B.1.1. Water cooled reactors

Water cooled reactors (WCRs) have played a significant role in the commercial nuclear industry since its inception, notching up over 16 000 reactor-years of operation, and they currently account for more than 95% of all operating civilian power reactors in the world. Of the 65 nuclear reactors under construction, 63 were light or heavy water cooled.

Major developments in the WCR sector in 2015 involve four new constructions, eight new grid connections, power uprates at existing plants and continually increasing capacity factors in all types of WCRs, as well as proposed new plants for countries that do not yet operate any commercial reactors.

An economically competitive way to raise nuclear capacity in a country is by increasing the authorized power output from existing plants. All advanced WCRs have increased power outputs, with recent constructions varying from 1000 to 1650 MW per unit (Fig. B.1). Furthermore, a clear trend is towards multi-unit sites with single or multiple types of reactors, underscoring the economies of scale for commercial nuclear reactors.

Advanced versions of existing WCRs are also increasingly being considered, studied and implemented in several countries for the gradual deployment of advanced and more efficient, either partially or fully closed, fuel cycles.

FIG. B.1. WWER-1000 NPP under construction at the Kudankulam nuclear site.

Several Member States are conducting research and development (R&D) on supercritical water cooled reactors (SCWRs). The conceptual designs for the Canadian SCWR, a heavy water moderated pressure tube reactor concept, and the Chinese SCWR (CSR1000) were completed. In Europe, a concept for a European high performance LWR was launched some years ago. In the Russian Federation, conceptual studies on WWER-SCP are ongoing, including the possibility of a fast spectrum core.

The IAEA continues to maintain and update its Advanced Reactors Information System (ARIS), a database that includes information provided by the design organizations [B.1].

B.1.2. Fast neutron systems

Since 1960, significant fast reactor development and deployment programmes have been pursued worldwide, bringing the knowledge on fast reactor and associated fuel cycle technologies to a high level of maturity. There is increased global interest in developing these reactors because of their distinctive capability to provide an efficient, safe, sustainable and clean source of energy.

Sodium cooled fast reactors (SFRs), lead cooled fast reactors (LFRs), lead–bismuth cooled fast reactors (LBFRs) and gas cooled fast reactors (GFRs) are currently being developed at national and international levels in compliance with higher standards of safety, sustainability, economics, physical protection and proliferation resistance. In addition, the molten salt fast reactor (MSR) concept is being considered as a long term option.

The most mature fast reactor technology, the SFR, has more than 400 reactor-years of experience acquired through the design, construction and operation of experimental, prototype, demonstration and commercial units operating in a number of countries, including China, France, Germany, India, Japan, the Russian Federation, the UK and the USA.

The Russian BN-600 SFR has shown an impressive operational performance by reaching an 86% load factor in 2014. The BN-800 SFR (Fig. B.2) was connected to the grid in 2015. The final design of the innovative BN-1200 has been completed. In May 2015, the sodium cooled Multipurpose Fast Research Reactor obtained a construction licence from the regulatory authority and preliminary civil engineering works were completed; it is supposed to replace the BOR-60 reactor in 2020. With regard to heavy liquid metal technology, the engineering designs have been completed for the BREST-OD-300, an advanced LFR concept, and the SVBR-100, a lead–bismuth cooled modular fast reactor.

In India, the Fast Breeder Test Reactor has been in operation since October 1985; the construction of the 500 MW(e) Prototype Fast Breeder Reactor has been completed and the commissioning is under way, with first criticality expected in 2016. India is planning to construct two more fast breeder reactors at the same site.

The first stage of Chinese fast reactor technology development has been achieved with the China Experimental Fast Reactor reaching 100% power in December 2014. The innovative CFR-600 is planned to be in operation in 2023. China's lead based CLEAR-I reactor is also under preliminary engineering design.

In Japan, the experimental fast reactor JOYO and the SFR prototype Monju are in long term shutdown. Phase II of the Fast Reactor Cycle Technology Development programme, which includes the demonstration of key technologies as well as the conceptual design of the Japan sodium cooled fast reactor, is also suspended.

In the Republic of Korea, the preliminary design of the Prototype Generation IV Sodium Cooled Fast Reactor is being carried out, along with supporting R&D activities. The preliminary safety information document was submitted to the Korean Nuclear Regulatory Authority by the end of 2015.

In Europe, the concepts under development are: ASTRID, the French industrial prototype of a Generation IV SFR; ALFRED, the European demonstrator of a Generation IV LFR; ALLEGRO, the experimental GFR; and MYRRHA, a lead–bismuth cooled pilot research reactor based on an accelerator driven system. ASTRID will reach the end of the conceptual design phase by the end of 2015. MYRRHA has reached the second phase of the front end engineering design.

FIG. B.2. The BN-800 commercial fast reactor at the Beloyarsk NPP, Russian Federation, was connected to the grid in December 2015. (Photograph courtesy of Rosenergoatom.)

In the USA, the fast reactor efforts are mainly focused on building base technical capabilities and some innovative technology options. With a vast set of experimental data coming from the former operation of a number of experimental SFRs, the US Department of Energy is supporting R&D activities, including in the fields of advanced materials, safety and innovative fuels. Private firms are also investigating fast reactor designs.

B.1.3. Gas cooled reactors

The end of an era for the first generation of gas cooled reactors (GCR) was reached when Wylfa 1, the last remaining Magnox reactor, ceased operation at the end of 2015. The UK continues commercial operation of 14 advanced GCRs. Many Member States are still pursuing the development of high temperature gas cooled reactors (HTGRs). Such reactors use coated particle fuel, can achieve very high burnup, operate at higher temperatures (≥ 700°C) and use helium as coolant. Only smaller modular HTGR concept designs are currently considered so that the reactor can solely rely on inherent safety features instead of active engineered safety systems. Near term deployment for efficient electricity generation as well as for cogeneration, to serve a huge process heat market, is being considered.

In China, the construction and main component manufacturing of the HTR-PM are progressing well (Fig. B.3). This 200 MW(e) industrial demonstration power plant consists of two 250 MW(th) reactor units and is expected to be in operation by the end of 2017. A 600 MW(e) commercial plant

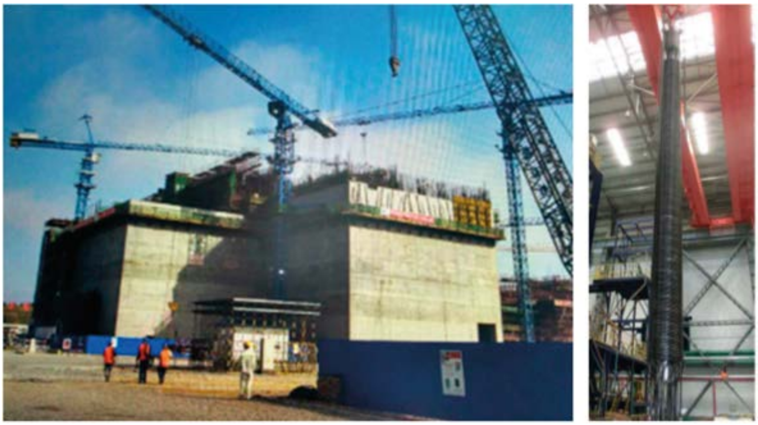

FIG. B.3. Construction site (left) and the steam generator (right) of the HTR-PM at Shidao Bay, Weihai City, China. (Photographs courtesy of Institute of Nuclear and New Energy Technology.)

is being designed and possible sites have been identified. The industrial scale fuel manufacturing technology has been established and international fuel sphere irradiation tests were completed in 2014, with tests at accident conditions planned. The construction and commissioning of the new fuel fabrication plant in Baotou have been completed, and manufacturing is planned to start in 2016.

The National Nuclear Energy Agency in Indonesia completed the concept design and preliminary safety analysis report for the 10 MW(th) pebble bed experimental power reactor and submitted the initial site evaluation to the regulator. Future commercial deployment for cogeneration is also foreseen.

In Japan, once the regulatory review to restart the 30 MW(th) High Temperature Engineering Test Reactor (HTTR) has been completed, further safety demonstration tests and the coupling to a helium gas turbine and a hydrogen production plant are planned.

In the USA, HTGR activities continued as part of the Department of Energy's Advanced Reactor Concepts programme. They focus on fuel qualification, on graphite and high temperature materials qualification, on test facilities to illustrate passive safety characteristics and on developing the licensing framework. Private firms are also developing GCR designs.

Some activities related to HTGRs are under way in Kazakhstan, South Africa, Ukraine and the European Commission. Preparations to be able to heat the ASTRA critical facility to different temperatures continue in the Russian Federation and the first irradiation test of coated particle fuel was done in the Republic of Korea.

B.1.4. Small and medium sized or modular reactors

There is increasing interest in SMRs and their applications. In the past decade, the focus has been on advanced modular reactors. Representing major lines and coolant types, they can produce up to 300 MW(e) power and their components can be factory fabricated and transported as modules to sites or utilities as demand arises. The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil fired units, enhancing safety performance through passive safety features, and offering better economic affordability. There are about 50 SMR designs and concepts globally. Most of them are in various developmental stages and some are claimed as being near term deployable, as shown in Fig. B.4. There are, however, three SMRs under construction in Argentina, China and the Russian Federation.

Many near term deployable SMRs are of the integral pressurized water reactor (iPWR) type. There are three SMRs in advanced stages of construction: in the Russian Federation, the KLT-40S, a PWR based transportable nuclear power

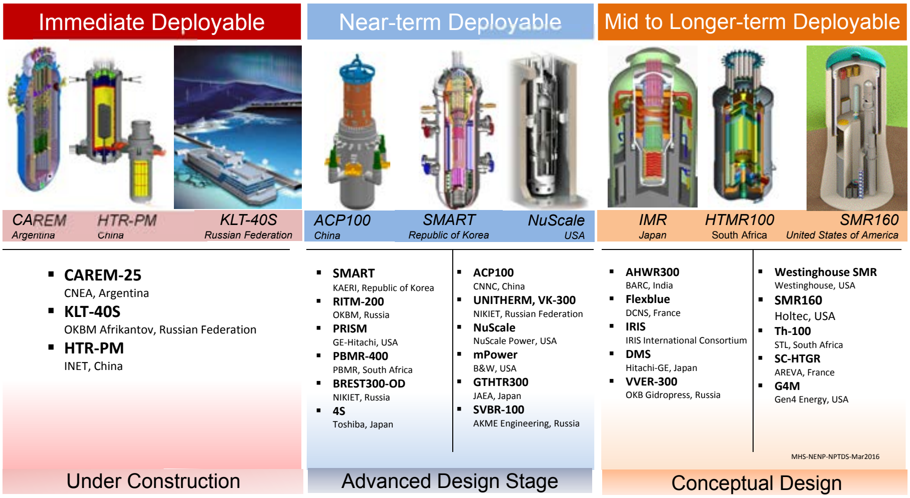

FIG. B.4. Status of SMR deployment.

plant (TNPP) with a capacity of 35 MW(e) per module is expected to produce electricity and be connected to the grid by 2019; in Argentina, a prototype natural circulation iPWR with a capacity of 31 MW(e) called CAREM-25 is expected to be ready for startup commissioning and criticality in October 2018; and in China, the gas cooled HTR-PM comprising two 250 MW(th) reactors to deliver 200 MW(e) is expected to be in operation by the end of 2017 as an industrial demonstration power plant.

With regard to SMRs intended for near term deployment, in the Republic of Korea, the system-integrated modular advanced reactor (SMART), an iPWR delivering 100 MW(e), received a standard design approval from the country's Nuclear Safety and Security Commission in 2012. In September 2015, a pre-project engineering agreement was signed for the deployment of a SMART reactor in Saudi Arabia.

In China, the ACP100 reactor, an iPWR with a capacity of 100 MW(e), is undergoing the IAEA's Generic Reactor Safety Review. An industrial demonstration plant with two 310 MW(th) units is planned in Fujian Province.

The Russian Federation has several other near term deployable SMR designs for floating TNPPs, including the RITM-200 to produce 50 MW(e), the ABV6-M — a natural circulation SMR to generate 6 MW(e) — and the VBER-300 with an electric power output 300 MW(e).

In the USA, NuScale Power is preparing a design certification application to the NRC for its NuScale reactor design in the last quarter of 2016. It is a natural circulation iPWR made up of 12 reactor modules, each with a net electric power of

50 MW(e). Another iPWR design is the BWX Technologies/Bechtel's Generation mPower twin module reactor with a rated power of 180 MW(e) per module. The Westinghouse SMR to generate 225 MW(e) and Holtec's SMR-160 with natural circulation to produce 160 MW(e) are also under development.

In Japan, 4S ('Super-Safe, Small and Simple') is a sodium cooled reactor without on-site refuelling. The 4S offers two outputs: 30 and 135 MW(th) as a distributed energy source for multipurpose applications. The Modular Simplified and Medium Small Reactor (also referred to as DMS) is a natural circulation BWR-type SMR with an electrical output of 300 MW(e).

There are numerous SMR designs that are in conceptual design stages: in India, the AHWR300-LEU, a pressure tube heavy water reactor with a capacity of 304 MW(e) and a naturally circulated primary system, is under development.

In France, Flexblue is a transportable, seabed moored SMR with a capacity of 160 MW(e) per module. Flexblue is designed to be remotely operated from an onshore control room.

In Canada, the Integral Molten Salt Reactor (IMSR) is under development and offers three designs: IMSR80, IMSR300 and IMSR600 with electrical capacities of 32.5 MW(e), 141 MW(e) and 291 MW(e), respectively. Molten salt reactors are also being designed by commercial groups in several other countries.

B.1.5. International initiatives on innovative nuclear energy systems

Owing to increasing concerns over resource availability, climate change and energy security, a number of international initiatives on innovative nuclear energy systems have been launched in the last decades.

Recognizing the need to take action to ensure that nuclear energy was developed in a sustainable manner, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated in 2000 as an IAEA project. In 2015, Thailand became the 41st member of INPRO, which brings together technology holders and users to jointly consider international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles.

Three manuals on sustainability assessment in the areas of economics, infrastructure and environmental effects, including depletion of resources, were published in 2014–2015 as IAEA Nuclear Energy Series publications. Nuclear Energy System Assessments based on the INPRO methodology are ongoing in Indonesia, Romania and Ukraine.

The Generation IV International Forum (GIF) is a cooperative international endeavour organized to carry out the R&D needed to establish the feasibility and performance capabilities of the next generation of nuclear reactors. With 13 members, the GIF focuses on six nuclear energy systems as described in its

Technology Roadmap for Generation IV Nuclear Energy Systems of 2002 [B.2] and in its 2014 update [B.3]: GFRs, very high temperature reactors (VHTRs), SCWRs, SFRs, LFRs and MSRs.

The GIF members interested in implementing cooperative R&D on one or more of the selected systems engage in common R&D projects, with well defined deliverables, milestones and time schedules, and within a clearly defined contractual framework.

The GIF and INPRO members hold annual interface meetings focusing on specific assessment methodologies in the areas of economics, proliferation resistance, and risk and safety. They also exchange information about ongoing projects on the six selected reactor technologies.

Another important activity in the area of SFRs launched in 2011 by the GIF, in cooperation with the IAEA, is the development of safety design criteria (SDC) and the efforts undertaken to harmonize these with safety design guidelines among the design organizations represented within the GIF, as well as to quantify the high level of safety expected for SFR Generation IV systems. A first version of the SFR SDC was published in 2014. The extension of this activity to other Generation IV systems, such as VHTRs and LFRs, is under consideration.

The Sustainable Nuclear Energy Technology Platform (SNETP), launched by the European Union (EU) in 2007, promotes research, development and demonstration for the nuclear fission technologies necessary to achieve the European Strategic Energy Technology Plan. The SNETP Strategic Research and Innovation Agenda and Deployment Strategy have been recently updated. The SNETP gathers over 100 European stakeholders from industry, research, academia, technical safety organizations, non-governmental organizations and national representatives.

Under the framework of SNETP, the European Sustainable Nuclear Industrial Initiative, launched by the EU in 2010, addresses the European need for the demonstration of Generation IV fast neutron reactor technologies, their supporting research infrastructures, fuel facilities and R&D work. It focuses on developing two parallel technologies: the sodium cooled fast neutron reactor technology as the reference solution, with the start of construction of a prototype around 2020 in France that will strongly support this technology (ASTRID); and alternative lead cooled fast reactor (ALFRED) and GFR (ALLEGRO) technologies. In addition, a lead–bismuth irradiation facility (MYRRHA) will support the fast reactor technology deployment, including actinide recycling for transmutation.

B.1.6. *Non-electric applications of nuclear power*

The use of nuclear energy for non-electric applications, especially for seawater desalination, hydrogen production, district heating, tertiary oil recovery and other industrial applications, is of broad interest to several Member States.

The technologies required for cogeneration (i.e. electricity and process heat production) have already been demonstrated and proven (see Fig. B.5). For nuclear cogeneration, significant experience exists in the categories of district heating and seawater desalination with a total accumulated experience of more than 750 operation years from 74 nuclear reactors. Current NPPs in nuclear cogeneration mode can achieve an increase of the overall thermal efficiency by more than 30%, a reduction in power generation cost by as much as 20% and better electrical grid flexibility. When innovative advanced energy systems designed for very high coolant exit temperatures become available, a number of industrial processes, such as hydrogen production, requiring high temperature heat or steam, will benefit from a very reliable, abundant and sustainable energy source.

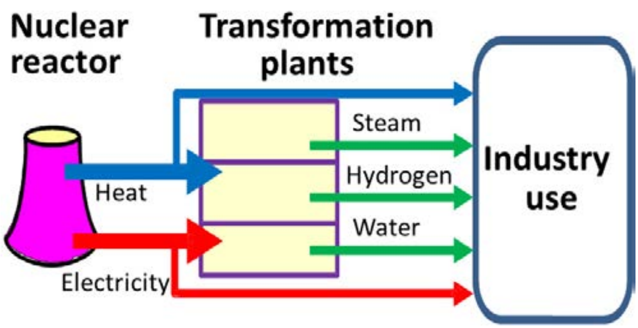

FIG. B.5. General scheme for coupling a nuclear reactor to an on-site industrial plant.

Recently, the Russian Federation signed agreements with Algeria, Egypt and Jordan, and is in discussion with Saudi Arabia, for the use of nuclear power for seawater desalination. Saudi Arabia has signed a memorandum of understanding with the Republic of Korea for two SMART 330 MW(th) PWRs to be used for cogeneration, including seawater desalination, and is discussing with France future plans for seawater desalination using nuclear energy. The twin PWRs of Diablo Canyon NPP in California, USA, can produce nearly 1.5 million gallons per day of potable water, but uses only 40% of this capacity for on-site consumption. Having its operating licences extended to 2024 and 2025, and in light of recent harsh drought, the operator agreed in May 2015 to provide water to the host county to help fight wildfires. Integrating this potable water into public water systems is also under consideration.

Hydrogen production is the subject of a wide range of activities, notably in the USA and the EU. The aim is to open the application of nuclear energy to the transportation sector and reduce the present reliance on fossil fuels with the associated price volatility, finite supply and greenhouse gas emissions. Research and development programmes are ongoing in several countries and some experience in high temperature applications of nuclear energy is available on a laboratory scale, also from component tests in earlier HTGR programmes. Having successfully developed and operated the 30 MW(th) HTTR, Japan is building on the HTTR through a project to demonstrate the cogeneration of both electricity by a gas turbine and of hydrogen using a thermochemical water splitting process. This system is expected to go into operation in 2022. The project aims to fully develop the system technology including a licensing database required for the planned construction in 2030 of the commercial plant GT-HTR300 for the cogeneration of hydrogen and desalination. The HTR-PM, under construction in China, can be used for either process steam or hydrogen production. Other R&D work with the involvement of industry is continuing in Canada, India, the Republic of Korea and in other States.

The EU energy policy and main goal of decarbonization by 2050 could make Europe the first place to implement nuclear cogeneration on a large scale. With its large industrial market, Europe is showing increasing interest in the use of nuclear cogeneration in refineries, chemical plants and other industries, where fossil fired cogeneration plants can be directly replaced by nuclear reactors offering simultaneously large amounts of process steam and electricity. A study conducted in France showed that presently operating nuclear reactors could be easily modified to efficiently supply large scale heating networks. Such a step could open a new perspective in energy management and pave the way for future abundant energy savings.

B.2. Fusion

Providing energy from nuclear fusion is widely regarded as the grand engineering challenge of the twenty-first century. With the establishment of the ITER project in 2006, China, India, Japan, the Republic of Korea, the Russian Federation, the USA and the EU have joined efforts to demonstrate the scientific and technological feasibility and safety features of fusion energy production in excess of 500 MW for peaceful purposes.

Years of hard work by all ITER parties are bearing fruit as the facility takes shape and progress on all fronts is made. The completion of the first floor of the Tokamak complex (with a surface of 9600 m^2 and a thickness of 1.5 m of reinforced concrete consisting of four successive layers — two of 50 cm, one of 30 cm and one of 20 cm) in the last quarter of 2014 has marked the end of a major civil works contract and the beginning of the construction phase (Fig. B.6).

FIG. B.6. Aerial view of the ITER construction site in August 2015 (left). As of 21 October 2015 (right), the 200° segment of the ITER bioshield, the 3.2 metre thick 'ring' that will surround the machine, was constructed. (Photographs courtesy of ITER.)

With an infrastructure complying with French nuclear safety requirements, ITER will be the largest nuclear facility in France and the first ever nuclear fusion facility in the world. In May 2015 the project reached a construction milestone as the first plant components — two out of a total of four electrical transformers that will connect the 400 kV grid to the alternating current power distribution system — were installed in their permanent positions.

Even as the partners tackle the formidable challenges of ITER, the need to understand the scientific and technical issues for going beyond ITER, and the need to start addressing them now, is widely appreciated. Collectively, the activities to develop solutions for harnessing fusion energy comprise a demonstration fusion power plant (DEMO) programme.

The third IAEA DEMO programme workshop was held from 11 to 15 May 2015 on the campus of the University of Science and Technology of China, Hefei, China, with the objective being to discuss a subset of key DEMO scientific, technical and programmatic issues, and to define the facilities and programme activities that can lead to their resolution. A related aim was to identify opportunities to make greater progress through international collaboration.

Outcomes of the workshop indicated that ITER's main contribution to the fusion programme will be to advance the understanding of the physics of a burning plasma. In addition, ITER will make significant progress on challenging plasma stability and control issues, including prediction and avoidance or mitigation of major plasma disruptions and control of edge localized modes.

In power exhaust technology, ITER will help establish the effects of long term exposure of plasma facing components to plasma, such as ion damage to first wall and divertor materials. As DEMO will use heating and current drive systems similar to those used in ITER, ITER will provide direct demonstrations of technical feasibility for several key components beyond the ITER project. Finally, ITER will contribute to blanket technology through the Test Blanket Module programme. Experience shows that the technical design and integration analysis need to be as detailed as possible and all validation and qualifications should be established before issuing the preliminary safety analysis to the regulator. ITER will provide a comprehensive physics and technology database for DEMO designers to use that will support the analysis required to satisfy the need for detail in the preliminary safety analysis.

Several ITER parties have turned their attention to studies on integrated devices intended to move beyond ITER. In contrast to ITER, these studies are national and are currently only at a preconceptual stage of design. Table B.1 summarizes information on four such devices, as presented at the workshop.

These studies hold the potential for impressive strides towards a DEMO by the middle of this century, but quantitative measures of expected progress against a complete set of DEMO readiness metrics are needed to assess the gaps that might remain even if all these projects were successfully carried out. It should be noted that there are general gaps for these machines themselves, especially their later phases, for which R&D is necessary in the near term.

Open questions exist on some key issues, including burning plasma physics and control, materials and component technologies, machine availability, and magnetic configuration options. It was generally recognized that no single device is likely to resolve all DEMO issues simultaneously but at the same time it is not clear how many machines are needed, nor how diverse an optimal portfolio should be. Therefore, there would appear to be a significant advantage in implementing an international strategy for the planning and coordination of work to improve coverage of DEMO needs that are currently not adequately addressed, to reduce duplication, and to be more robust against technical setbacks and delays.

TABLE B.1. CURRENT MISSION AND PERFORMANCE GOALS OF PLANNED NEXT STEP INTEGRATED FUSION DEVICES BEYOND ITER

	EU DEMO	JA DEMO	K-DEMO	CFETR (Phase I)
Mission	Net electricity ($Q_{eng} > 1$) Tritium self-sufficiency	Net electricity ($Q_{eng} > 1$) Tritium self-sufficiency	Net electricity ($Q_{eng} > 1$) Tritium self-sufficiency Materials and component testing in fusion environment	Materials and component testing in fusion environment Full tritium fuel cycle
P_{fus}	2000 MW	1500 MW	≥ 300 MW	50–200 MW
TBR	> 1.0	> 1.05	> 1.0	≥ 1.0
Pulse length	2 hrs	2 hrs to steady state	steady state	1000 s to steady state
Duty factor	~ 70%			30–50%
P_{elec}	500 MW	200–300 MW (net)	≥ 150 MW (net)	N/A
Tritium breeding	To be determined — solid and Li–Pb breeder under consideration	Solid breeder, PWR technology	Solid breeder, PWR technology	Solid breeder, PWR technology, close tritium cycle at ~ 1/10 DEMO scale
Magnetic configuration	Tokamak	Tokamak	Tokamak	Tokamak
Maintenance	Remote handling	Remote handling	Remote handling	Remote handling

Note: EU DEMO (Europe); JA DEMO (Japan); K-DEMO (Republic of Korea); CFETR (China); Q_{eng}: engineering power amplification factor; P_{fus}: fusion power; TBR: tritium breeding ratio; P_{elec}: electric power.

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C. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

C.1. Accelerators

C.1.1. High power proton accelerators

There is increasing demand for high power proton or ion beam accelerators in various fields, such as particle, nuclear and neutron based physics, and in the transmutation of long lived nuclear waste. These applications typically require beams with very high average power and energy in the GeV range, which goes significantly beyond the capability of most existing facilities. Figure C.1 shows current and planned projects that are pushing beam powers towards 10 MW [C.1].

Accelerator-driven systems (ADSs) are possible solutions for dedicated transmutation facilities based on a multi-MW superconducting proton linear accelerator with enhanced reliability capabilities. The Belgian MYRRHA project, cofinanced by, inter alia, the EU, and the Chinese ADS Project are opportunities to demonstrate ADS technology at high power within 10–15 years.

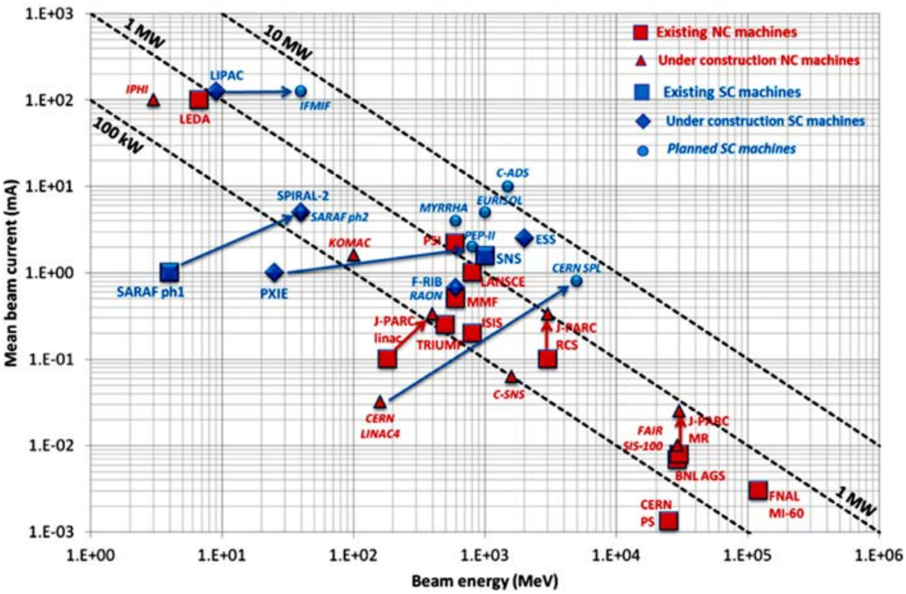

FIG. C.1. High power proton/neutron beam projects around the world. Graph by BIARROTTE, J-L./CC BY 3.0, reproduced from Ref. [C.1].

C.1.2. Ion beam techniques roadmap

Accelerator based ion beam techniques (IBTs) encompass a suite of analytical and modification techniques in which energetic (0.1–100 MeV) beams of charged particles (Z = 1, 2 and higher) are directed onto a material to be analysed or modified. Such techniques have been used for over 50 years, and much of the underlying physics, data and machinery are mature. Advances in IBTs have led to contributions in many fields (Fig. C.2) — for example, in climate studies using cosmogenic isotopes, in developing enhanced materials and understanding the ageing of reactor components, and in the development of hadron therapy, which is likely to have huge consequences for human health.

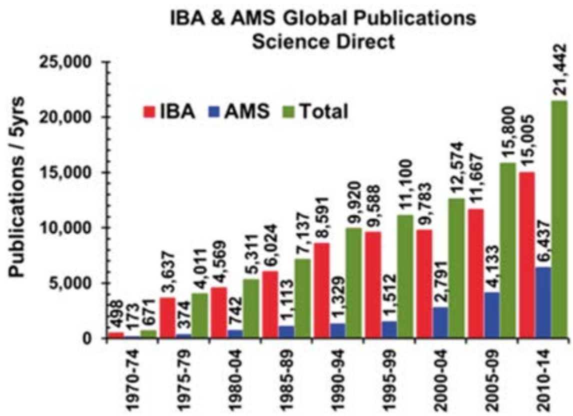

FIG. C.2. An increasing trend in the number of publications related to the utilization of IBT (IBA: ion beam analysis; AMS: accelerator mass spectrometry). (Figure courtesy of D. Cohen, Australian Nuclear Science and Technology Organisation.)

The IAEA has taken the lead in coordinating the development of an IBT roadmap, which will include aspects of mid-term (5–15 years) strategic planning for accelerator science and associated technologies. Extensive discussions by international experts led to the first draft, setting up the priorities for technological developments and defining the corresponding metrics. The IBT roadmap is expected to be finalized in 2016. The relevant documents are available on the IAEA's Accelerator Knowledge Portal [C.2].

C.1.3. X ray techniques for materials characterization and imaging

Synchrotron radiation has been utilized for over thirty years to advance fundamental knowledge in multidisciplinary science and to foster technological applications. The fourth generation of synchrotron light sources will open new possibilities for scientists. Current projects include MAX IV in Lund, Sweden (full operations are expected to commence in 2016) and Sirius in Brazil (commissioning is expected in 2018). Recent progress in accelerator technology offers low emittance radiation and thus high brightness and better coherence. Breakthrough developments such as ptychography are expected in the field of high resolution X ray imaging, where image reconstruction with spatial resolutions far superior to those offered by conventional techniques is possible. These new synchrotron sources promote the parallel development of advanced pixelated, energy dispersive or single counting X ray detectors.

A good example is the 384 silicon diode array Maia X ray fluorescence (XRF) detector that has already been demonstrated at different synchrotron beamlines to provide fast elemental and chemical speciation imaging. Macro XRF imaging, with spatial resolution tailored by the incident synchrotron beam size, has found a prominent application in the examination of biological systems and works of art (Fig. C.3). Parallel developments in X ray optics and relevant methodologies can also offer spatially resolved analysis of large area specimens when irradiated by relatively broad X ray beams. The concept of full field X ray cameras is emerging rapidly as a promising analytical methodology that can be adapted at synchrotron sources, particle induced X ray emission beamlines or portable XRF spectrometers (Fig. C.4).

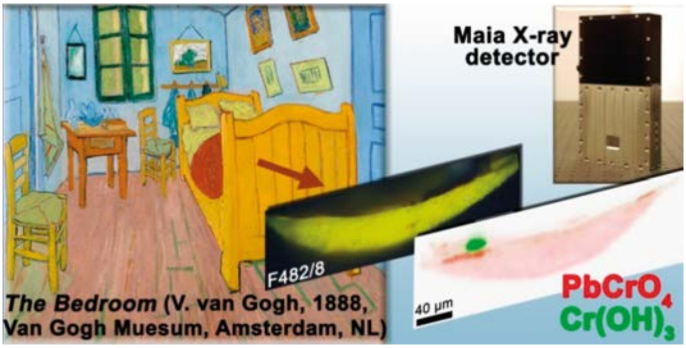

FIG. C.3. Full spectral XANES imaging using the Maia detector array to study the alteration process of chrome yellow pigments in paintings by V. van Gogh (figure reproduced from Ref. [C.3] with permission from the Royal Society of Chemistry).

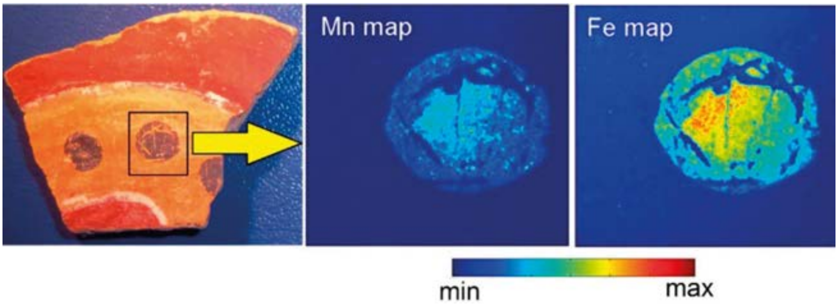

FIG. C.4. Full field particle induced X ray emission analysis of a manganese black decoration in polychrome pottery from the Nazca culture (Peru) at the National Institute of Nuclear Physics, Italy.

C.1.4. Combined ion and neutron beam techniques for trace element and molecular fingerprinting

The use of ion and neutron beam techniques for trace element analysis is well established, and such services are available through accredited laboratories in a number of Member States operating accelerators or research reactors. Applications include: analysis of hair, nails, skin, plant and animal matter for medical or biomedical purposes; identification of the provenance of glasses, agricultural/food products and cultural heritage objects; identification of sources of ammunition, gunshot residue, bullets and nuclear detonations; and identifying and tracking environmental pollution.

The IAEA is assisting the development of a multi-analytical approach by exploiting the synergies between ion beam and neutron beam methods for high-precision trace element and molecular analysis. In addition, high-resolution 2-D and 3-D mapping of trace elements in 'real' objects (e.g. those with surface roughness or wet samples) will be developed to determine the provenance of materials (Fig. C.5).

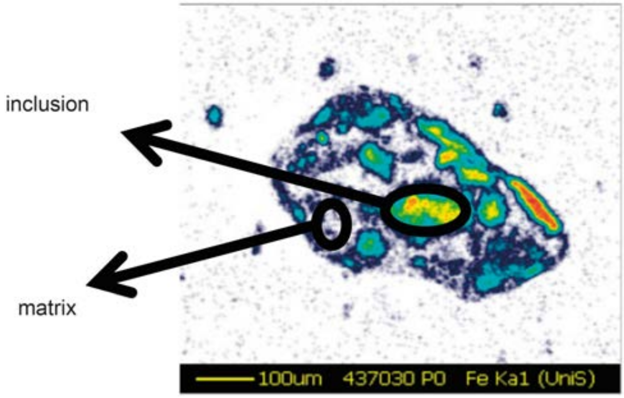

FIG. C.5. Two dimensional elemental image of α quartz sample measured by focused ion beams. The iron inclusions can be well separated from the matrix by allowing area selective determination of the stoichiometry, which is very useful for provenance purposes. (Figure courtesy of M. Baley, University of Surrey.)

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) to approximately 200 MW(th), still small 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.

To date, 754 research reactors have been built in 67 countries and 246 were operating in 55 countries as of 31 December 2015. The Russian Federation has the highest number of operational research reactors (63), followed by the USA (42), China (17) and France (10). Many developing countries also have research reactors (e.g. eight facilities operate in Africa). Worldwide, 58 research reactors operate at power levels higher than 5 MW and thus offer high neutron fluxes supporting high capacity applications.

Many operating research reactors still have a low utilization factor, and half of them are over 40 years old. Therefore, the majority require continuous attention for detailed strategic planning for utilization, ageing management, modernization and refurbishment. Efforts to enhance utilization and to yield additional revenues continue to grow. In the past two years, 33 research reactor facilities prepared and submitted strategic plans to the IAEA for review. The IAEA has also revised its guidelines on strategic planning for research reactors by including aspects of new research reactor or major refurbishment projects,

TABLE C.1. COMMON APPLICATIONS OF RESEARCH REACTORS AROUND THE WORLD [C.4]

Type of application [a]	Number of research reactors involved [b]	Member States hosting utilized facilities
Teaching/training	173	54
Neutron activation analysis	124	54
Radioisotope production	89	44
Material/fuel irradiation	73	28
Neutron radiography	71	40
Neutron scattering	48	32
Transmutation (silicon doping)	26	17
Geochronology	27	23
Transmutation (gemstones)	18	10
Neutron therapy, mainly R&D	18	12
Other[c]	128	36

[a] The IAEA publication Applications of Research Reactors [C.5] describes these applications in more detail.
[b] Out of 265 research reactors considered (246 operational, 19 temporarily shut down; as of November 2015).
[c] 'Other' includes calibration and testing of instrumentation, shielding experiments, nuclear data measurements, public visits and seminars.

and sharing experiences of well operated facilities through numerous examples. Among other areas, 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. In September 2015, the project was kicked off in Latin America (with Argentina as the host country) and in October 2015 in Europe and Africa (with France as the host country).

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, Brazil, France, India, Jordan, the Republic of Korea, the Russian Federation and Saudi Arabia. Several Member States have formal plans to build new research reactors, including Belarus, Belgium, the Plurinational State of Bolivia, the Netherlands, the USA and Viet Nam. Others, such as Azerbaijan, Bangladesh, Ethiopia, Ghana, Kuwait, Lebanon, Malaysia, Mongolia, Myanmar, Nigeria, South Africa, the Sudan, Tajikistan, Thailand, Tunisia and the United Republic of Tanzania are considering building new research reactors[3]. International cooperation has been established for the construction of multipurpose research reactors such as the Jules Horowitz Reactor in France and the Multipurpose Fast Research Reactor in the Russian Federation.

Research reactor regional networks and coalitions, facilitated by the IAEA[4], help foster international cooperation and enable research reactors to 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 Centres based on Research Reactor (ICERR) scheme. In 2015, the research centres of the French Alternative Energies and Atomic Energy Commission at Saclay and Cadarache were together designated the first ICERR, and additional applications for designation are expected to be received in 2016 from other organizations.

The US Department of Energy's Office of Material Management and Minimization, the successor of the Global Threat Reduction Initiative, continued throughout 2015 to carry out its mission to minimize the use of HEU in the civilian nuclear sector. By the end of 2015, 94 research reactors within the scope of implementation of the Office had been converted to LEU fuel or confirmed as shutdown, including one molybdenum-99 production facility that used HEU. Major successes include Jamaica's loading of the LEU fuel core into the Slowpoke-2 reactor, the discharge of the HEU fuel from China's prototype miniature neutron source reactor (MNSR) in preparation for conversion, and the insertion of Russian uranium–molybdenum LEU lead test assemblies into

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[3] The IAEA publication Specific Considerations and Milestones for a Research Reactor Project [C.6] and a set of supporting documents are aimed at helping Member States in this area.

[4] The IAEA supports several different research reactor coalitions in the Baltic, the Caribbean, Central Africa, Central Asia, Eastern Europe and the Mediterranean regions and in the Commonwealth of Independent States, as well as the Global TRIGA Research Reactor Network.

the MIR reactor in Dimitrovgrad for irradiation. The IAEA continued to support Ghana in its efforts to convert and transfer the HEU core of its MNSR, expected to occur in 2016.

High enriched uranium minimization activities include the return of HEU research reactor fuel to the country of origin where it was enriched. By the end of 2015, 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 2165 kg of fresh and spent HEU research reactor fuel. The non-irradiated Russian origin HEU from the Breeder-1 neutron source facility in Tbilisi, Georgia, was removed in December 2015. With the removal of the irradiated liquid HEU fuel from the IIN-3M FOTON reactor in Uzbekistan (Fig. C.6), 28 countries[5] that had HEU are now HEU-free.

FIG. C.6. Transport canister with irradiated liquid HEU fuel (left). The truck carrying the package with the container of liquid HEU fuel is driven into the cargo plane that repatriated the fuel from the IIN-3M FOTON reactor in Uzbekistan to the Russian Federation (right).

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 high density LEU fuels.

While there were no major shortages of molybdenum-99 in 2015, operational challenges at processing facilities and older research reactors continue. Because of changes in demand, efficiencies gained and diversification in supply, the minor unscheduled outages were well managed by the industry. The conversion of medical isotope production processes from HEU to LEU targets

[5] Plus Taiwan, China.

continued, with the Australian Nuclear Science and Technology Organisation (ANSTO) and NTP Radioisotopes, South Africa, as the major suppliers of LEU based molybdenum-99. ANSTO expects its new molybdenum-99 production facility to be completed in late 2016, which will increase production to 3500 6-day curies per week. NTP Radioisotopes is continuing to convert its processes to the exclusive use of LEU. The Institute for Radioelements in Belgium and Mallinckrodt Pharmaceuticals in the Netherlands continue to make progress in their conversion efforts. Although Canadian Nuclear Laboratories are pursuing an extension of operations of the National Research Universal (NRU) reactor until 31 March 2018, Canada intends to cease routine production of molybdenum-99 from the NRU reactor on 31 October 2016. Belgium's BR2 reactor, one of the major irradiators for molybdenum-99, was shut down in February 2015 for extended maintenance and modernization activities to prepare the facility for a 10 year extension of its operating licence beyond 2016. It is expected to resume normal operations in July 2016. The international molybdenum-99 community has worked successfully to adapt the production planning schedule to account for this extended outage. The Russian Federation also increased its production of molybdenum-99 in 2015.

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D. EMERGING INDUSTRIAL APPLICATIONS OF RADIATION TECHNOLOGIES

Radiation technologies are being tailored continuously for use in industrial applications, be it troubleshooting in a manufacturing plant, achieving improved quality in the production of high value materials or mitigation of pollutants in industrial effluents. This section will outline radiation technologies that have made a clear impact in recent years and enabled applications on an industrial scale.

D.1. Radiation technologies in industry and engineering

Thin layer activation is a nuclear technique that offers the possibility of on-line investigation into wear or corrosion on the scale of micrometres to nanometres in technologically advanced sectors such as the automobile industry, the energy industry and metallurgy. In a non-industrial context, coastlines and the seabed are subject to erosion, transport, sedimentation and consolidation processes. Radioisotope based tracers and sealed sources have often emerged as irreplaceable tools for sediment transport studies in marine environments, providing important parameters that allow for more effective design, maintenance and optimization of civil engineering structures, and can inform enhanced protection and management of coastal resources.

D.1.1. Thin layer activation for measuring wear, erosion and corrosion of materials

Nuclear techniques are widely used to investigate complex physical and chemical phenomena, including wear, mass transfer, corrosion and erosion. It is well known that the reliability of industrial equipment, transportation systems, nuclear and conventional power plants, and pipes, for example, is substantially influenced by degradation processes such as wear, corrosion and erosion. Consequently, the development of effective methods of detection, measurement and monitoring of the above processes is of great importance. Appropriate monitoring methods could prevent dangerous accidents during the operation of industrial installations and transport vehicles, and avoid production losses due to machinery breakdown.

When surfaces are not easily accessible or are concealed by overlying structures, nuclear techniques offer the most effective way of measuring and monitoring wear and corrosion. Thin layer activation, wherein only the surface layers of the desired parts of the machinery are activated by charged particles, provides a means to monitor key components despite their inaccessibility. The low activity levels involved allow for easy handling of the sample, and the achievable sensitivity of measurement is high.

There is constant progress in the application of tracer techniques in various branches of modern industry for the assessment of machine wear and corrosion, primarily owing to advances in the methods used for radioactive labelling of the component under investigation. Different labelling methods have been developed to measure nanometric scale material loss with relatively low activity, such as ultra thin layer activation, which relies on the recoil implantation of heavy radioactive nuclei produced by nuclear reactions and allows a surface loss measurement sensitivity of a few nanometres to be achieved.

D.1.2. Radiation technologies for investigating sediment transport

The investigation of sediment transport in seas and rivers is crucial for civil engineering and littoral protection and management. Coastlines and seabeds are dynamic regions with sediments undergoing periods of erosion, transport, sedimentation and consolidation. The main causes for erosion in beaches include storms and human activities such as the construction of sea walls, jetties, and the dredging of river mouths. Each of these actions disrupts the natural flow of sediment. Anthropogenic factors are now increasingly compounded by the effects of climate change. Although many current policies and practices may be accelerating the beach erosion process, there are viable options available to mitigate such damage and provide for sustainable coastlines.

Nuclear techniques can help in investigating sediment dynamics and in determining important parameters that allow for improved design, maintenance and optimization of civil engineering structures. The use of radioisotopes in tracers and sealed sources has proven particularly valuable in sediment transport studies.

Radiotracers are more sensitive and accurate than conventional tracers and are the only unequivocal method of direct real time assessment of sediment transport pathways. Various techniques for tracing and monitoring sediments using radiotracers have been developed by research groups in many countries.

In addition to radiotracers, sealed source techniques can provide information on the density of the sediments deposited in a navigation channel or harbour basins, as well as on the concentration of sediments circulating in suspension.

There are two typical problem areas where radiotracers and sealed source techniques can make an important contribution. These problem areas are the management of littoral zones that are subject to erosion, and of shorelines that undergo long term retreat, often resulting in beach loss; and in dealing with the improper selection of dumping sites for dredging operations at harbours, which may cause return of the dumped material to the dredged channel.

Since the environmental, economic and social benefits from the application of radiotracers and sealed source techniques for sediment tracing and monitoring are enormous, the IAEA facilitates technology transfer and offers training on a range of these techniques to its Member States.

Computational fluid dynamic (hydrodynamic) modelling is now a common tool for the management of natural systems and is increasingly used to study the fate and behaviour of particulates and contaminants. Radiotracer techniques are often employed to validate hydrodynamic models to enhance confidence in the predictive value of the models. Experimental tracing and numerical modelling are complementary methods of studying complex systems. Tracer data are based on direct observation, but are limited to the labelled component of the system and to a restricted domain of space and time. Numerical models can, in theory, accommodate all the important parameters, but are limited by their underlying assumptions and accessible computing power. Individually, both approaches have limitations, but together they offer a very powerful method of investigating complex systems. Over the past few years it has become clear that the synergistic use of modelling and radiotracer studies in the field can make a significant contribution towards addressing complex problems in natural systems.

D.2. Radiation technologies for the development of 'green' products and processes

Various industrial sectors are striving to become more environmentally friendly by producing higher performing products with lower energy consumption. Radiation processing techniques have a successful history in contributing to the development of innovative 'green' products and processes. This subsection will focus on novel radiation processed products such as radiation synthesized nanoscale materials in various shapes and sizes (nanoparticles, nanofibres, nanopores) that are envisaged for use in the preparation of active packaging for food and wound dressing materials, as well as for use as drug delivery devices. Concerns about the environmental pollution associated with the chemicals traditionally used in the coating and curing industry are the main drivers behind efforts to harness low energy electron beam radiation in order to manufacture such products.

D.2.1. Nanoscale radiation engineered materials

The radiation initiation of reactions (polymerization, cross-linking, controlled degradation and grafting) is a powerful tool for synthesis and/or modification of materials on the nanoscale, since this method enables the creation of new properties at any temperature and without toxic additives or residues that would need to be painstakingly and expensively removed afterwards. This is especially advantageous when the product is intended for medical applications. Additionally, such materials can be prepared from wastes, for example, carbon nanotubes have been successfully produced from discarded plastic bags.

D.2.1.1. Medical applications

Advances in the preparation and tailoring of nanoparticles have resulted in a range of products that can be used widely in health care and are in strong demand. Many nanoscale systems such as quantum dots, organic and inorganic nanospheres, dendrimers, liposomes and polymer nanoparticles have been proposed for medical applications. Nanogels — cross-linked polymer networks of nanoscale dimensions — present unique advantages in terms of flexible shape, large surfaces with multiple conjugation sites, internal space or pockets for carrying drugs that can be released in response to certain stimuli, and the possibility of internalization by human cells. The radiation synthesis of such nanogels was pioneered in Poland, and the method was quickly adopted by many researchers worldwide, including, inter alia, in Argentina, Brazil, Italy, Thailand and Turkey. Such nanogels can be prepared using synthetic or natural polymers, as well as biomolecules such as proteins and peptides. Besides their use as carriers for a specific drug payload to be released in situ to battle various diseases, nanoparticles are being incorporated in wound dressings to speed up healing and fight infections. Controlled radiation degradation is used successfully to prepare nanoporous polymer membranes, which can additionally be functionalized in order to prepare membranes that can selectively filter and separate various biomolecules.

D.2.1.2. Advanced coating and packaging materials for food

A recent survey reported that shelf life, freshness and quality of food are priorities for consumers [D.1]. ‘Active’, or ‘intelligent’, packaging is being developed in response to such needs. For example, films with superior gas barrier properties that can prevent oxygen from entering and inert gases from leaving the package have been shown to be effective in extending the life of the product without the loss of freshness. Films of this kind can be made by incorporating specific nanoparticles into the film, which could also contain enzymes, anti-bacterial agents and other components that help to control food degradation and spoilage. Such biologically active food packaging was prepared in Egypt from cellulose acetate by incorporating silver nanoparticles, while packaging with decreased oxygen and water vapour permeability was made from polycaprolactone and chitosan films by addition of graphene oxide.

Egyptian scientists are also working on the production of intelligent packaging for seafood by incorporating polyaniline nanofibres into polycaprolactone films. Such packaging changes colour when interacting with vapour emanating from decaying seafood, thus indicating clearly the freshness of the food or its loss. In Canada, nanocellulose is added to packaging made from biosourced materials to provide reinforcement as well as to make the material amenable for further chemical modification to suit specific packaging needs.

D.2.2. Radiation curing

The printing and coating industry worldwide is in search of environmentally safer procedures that use fewer or no solvents and thus avoid pollution, as well as the migration of degraded toxic by-products into consumer goods. The 2007 European Commission Directive 2007/19/EC — the Fourth Amendment to Directive 2002/72/EC [D.2], commonly referred to as the Plastics Directive — which established a maximum level of 10 parts per billion for the migration of non-authorized substances into food — is an example of a recent development that has prompted the packaging industry to look for new technologies. The growing demand for environmentally friendly processes and materials that can replace harmful ones has been a leading factor in the emergence of the use of low energy electron beam accelerators with energies of less than 300 keV for the coating industry. The use of radiation curable monomers and oligomers in coatings, inks and adhesives that polymerize and cross-link, avoids the use of volatile organic compounds for curing, thus enabling the coating and related industries to comply with clean air requirements by achieving significantly reduced emissions of toxic air pollutants during production and much lower levels of toxic chemicals in the product. Apart from these advantages, electron beam cured products and processes save energy and space, while increasing quality and productivity.

The wider application of radiation curing technology in the printing and coating industries necessitates continuous developments in accelerator technology to make the use of electron beam technology commercially viable on an industrial scale. The recent development of a new generation of highly compact and easy to operate electron beam emitters with an accelerating voltage range of 80–200 kV and treatment widths of up to 60 cm has the potential to further promote the use of this technology as it will allow the development, optimization and continued evolution of new products and processes across a wide range of applications such as curing and material development through cross-linking.

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E. ADVANCES IN MEDICAL IMAGING TECHNOLOGY

Advances in medical imaging technology for body composition assessment allow the quantification of parameters such as fat mass, lean mass and bone mineral density, as well as specific organ and tissue masses, including adipose, muscle and visceral mass. Body composition assessment is used in a number of applications from monitoring fitness to disease status and risk management. There is growing evidence that the individual components of body composition have a significant influence on chronic disease risk, disease progression, treatment response and health outcomes. Consequently, there is considerable interest in the ongoing development of body composition assessment tools and risk models to predict adverse outcomes. Currently, there are three imaging modalities widely used for body composition assessment: dual energy X ray absorptiometry (DXA), quantitative computed tomography (QCT) and magnetic resonance imaging (MRI).

E.1. Recent advances in imaging technology for the assessment of body composition

E.1.1. Body composition as a health indicator

Worldwide prevalence of overweight and obesity has shown alarming growth over the past several decades. The World Health Organization estimates that there are almost 2 billion overweight adults worldwide, of which over 600 million are obese — a figure that has doubled since 1980 [E.1]. These metabolic conditions have long since reached epidemic proportions in both adult and child populations. Obesity has been directly linked to several chronic health conditions such as diabetes, cardiovascular disease, osteoarthritis and cancer that severely affect quality of life and life expectancy. The economic costs of overweight and obesity are projected to double every ten years and to lead to significant increases in total health care expenditure.

Much emphasis is placed on accessible tools to assess health risk related to obesity. These are mostly non-imaging methods that are inexpensive and easy to use, including methods for obtaining obesity indices based on various combinations of height and weight such as body mass index (BMI), body shape index, body roundness index, and anthropometric indicators of obesity such as waist circumference and waist to hip ratio. However, to elucidate the underlying causal mechanisms between body composition and disease, more sophisticated body metrics are often necessary. For example, while the World Health Organization classifies overweight and obesity using BMI, this measure does not capture information about the relative amounts of fat and lean tissue, nor does it provide information about adiposity distribution throughout the body, both of which have been shown to be independently associated with metabolic syndrome. A step further in the quantification of body composition is the use of methods capable of quantifying whole body compartments of fat and lean masses, such as bioelectrical impedance analysis and air displacement plethysmography. However, these are incapable of isolating individual tissue compartments. Truly 2-D and 3-D imaging methods are necessary to subdivide the body into tissue types and spatial regions, and investigate association with disease, morbidity and mortality. Dual energy X ray absorptiometry, QCT and MRI are in broad use around the world for detailed body composition assessment. More recently, 3-D optical surface scanning has emerged as a novel tool for body composition analysis [E.2].

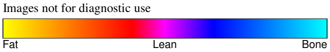
E.1.2. Advances in dual energy X ray absorptiometry

Dual energy X ray absorptiometry is a highly accurate and precise modality for measuring bone mineral density, bone mass, fat mass, lean soft tissue mass and fat percentage. The method involves simultaneous imaging at two distinct X ray energy levels. Leveraging the unique attenuation characteristics of different tissue types, DXA scans are used to calculate areal density properties from 2-D images. In DXA models, the bone mineral density is the bone mineral mass divided by the projected bone area in g/cm2. The fat mass is the lipid mass (triglycerides, phospholipid membranes, etc.) since all lipids have similar X ray attenuation characteristics. Until recently, DXA measures could not distinguish between tissue types such as skin, muscle, liver and subcutaneous and visceral adipose tissues (SAT and VAT). This is still mostly true; however, SAT and VAT are now reported for the lower abdomen using a specialized estimation algorithm. Furthermore, the measure of liver iron content by DXA has been shown to be accurate to reference standards [E.3]. A typical DXA report is shown in Fig. E.1.

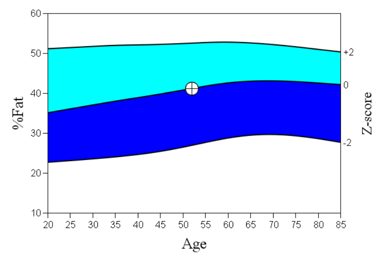
The radiation dose in DXA is very low, comparable to the dose from one day of background radiation (~8 μSV). However, with a properly trained technologist, DXA test–retest precision is very high: 1.0% coefficient of deviation or better for body fat percentage for repeat scans on the same individual [E.4, E.5]. DXA can report fat, lean soft tissue, and bone mineral mass compartments for anatomical subregions such as the arms, legs and torso. This is something that cannot be achieved with simpler non-imaging methods (bioimpedance analysis, air displacement plethysmography, etc.). However, there are limitations to DXA. One is that the three compartment model does not explicitly isolate water from the functional protein lean mass. Although hydration assumptions are not explicitly used by DXA to solve for body composition masses, changes in hydration status

Name: [redacted]	Sex: Female	Height: 165.9 cm
Patient ID: [redacted]	Ethnicity: White	Weight: 82.9 kg
DOB: [redacted]		Age: 51

Images not for diagnostic use

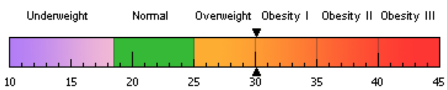


Total Body % Fat



Source: 2008 NHANES White Female

World Health Organization Body Mass Index Classification
BMI = 30.1 WHO Classification Obesity I



BMI has some limitations and an actual diagnosis of overweight or obesity should be made by a health professional. Obesity is associated with heart disease, certain types of cancer, type 2 diabetes, and other health risks. The higher a person's BMI is above 25, the greater their weight-related risks.

Body Composition Results

Region	Fat Mass (g)	Lean + BMC (g)	Total Mass (g)	% Fat	%Fat Percentile YN	AM
L Arm	2063	2297	4360	47.3	81	60
R Arm	1995	2474	4469	44.6	74	49
Trunk	12225	23281	35506	34.4	57	26
L Leg	8266	8669	16935	48.8	87	78
R Leg	8327	8615	16943	49.2	87	77
Subtotal	32877	45335	78212	42.0	74	49
Head	1327	3606	4934	26.9		
Total	**34204**	**48941**	**83145**	**41.1**	**75**	**50**
Android (A)	1597	3181	4778	33.4		
Gynoid (G)	5509	7386	12894	42.7		

Scan Date: June 01, 2016 ID: A06011609
Scan Type: a Whole Body
Analysis: June 02, 2016 12:37 Version 13.6
Auto Whole Body Fan Beam
Operator: es
Model: Horizon A (S/N 200228)
Comment:

Adipose Indices

Measure	Result	Percentile YN	AM
Total Body % Fat	**41.1**	**75**	**50**
Fat Mass/Height² (kg/m²)	12.4	77	59
Android/Gynoid Ratio	0.78		
% Fat Trunk/% Fat Legs	0.70	30	13
Trunk/Limb Fat Mass Ratio	0.59	13	4
Est. VAT Mass (g)	289		
Est. VAT Volume (cm³)	312		
Est. VAT Area (cm²)	59.9		

Lean Indices

Measure	Result	Percentile YN	AM
Lean/Height² (kg/m²)	16.9	78	70
Appen. Lean/Height² (kg/m²)	7.55	82	79

Est. VAT = Estimated Visceral Adipose Tissue
YN = Young Normal
AM = Age Matched

TBAR1209 - NHANES BCA calibration

HOLOGIC®

FIG. E.1. A typical body composition report is shown for a Hologic DXA system. Body composition results are reported for many subregions, including the arms, legs and trunk. Recent advances include the reporting of estimated VAT area, volume and mass in the lower abdomen, as well as several other lean indices, including the appendicular lean mass index. (Figure reproduced with permission of Hologic.)

are interpreted as a change in lean tissue mass. Since adipose also contains about 15% water by weight, monitoring change in muscle mass is confounded if adiposity also changes. Dual energy X ray absorptiometry is a specialized imaging modality not typically available on general use X ray systems because of the need for special beam filtering and near-perfect spatial registration of the two attenuations.

Dual energy X ray absorptiometry is more widely used for clinical trials than other body composition assessment methods. It is low dose compared with whole body computed tomography (CT) and it is inexpensive compared with MRI. Body fat percentage measurements from DXA are highly correlated to those obtained using CT and MRI ($r > 0.99$) [E.6], but are more precise. Depending on the scanner model and patient size, whole body scan times vary from 3 to 10 minutes. DXA systems of similar make and model can be easily cross calibrated in the field using standard biomimetic phantom materials such as stearic acid and water. Cross calibration between makes can currently only be done using standardization equations to take out systemic bias. Using a combination of phantoms and the standardization equations, pooling of data across clinical centres is possible. Lastly, large scale efforts have been undertaken to provide representative country specific metabolic health and nutrition samples including the National Health and Nutrition Examination Survey (NHANES) in the United States of America, and K-NHANES in the Republic of Korea.

E.1.2.1. Special DXA regions of interest

Since the inception of DXA, the subregions defined on whole body scans have been arms, legs, trunk and head for soft tissue reporting. However, in recent years, there has been progressive work to report special regions beyond these anatomical regions. Dual energy X ray absorptiometry systems can estimate visceral adipose fat as either a cross-sectional area or a tissue volume [E.7, E.8]. These VAT estimates are made by subtracting estimates of the overlying subcutaneous fat from the total android fat. The correlation between VAT measurements from DXA and CT is very high ($r > 0.90$).

E.1.2.2. Scanning obese patients with DXA

Scanning heavy patients on a DXA system has been challenging in the past owing to scanner weight limits and table dimensions. The weight limits for DXA scanner tables have recently been increased to 227 kg on some models. Specialized scan modes with slightly higher dose for obese patients are also available. In cases where it is difficult to fit an obese patient within the scan region, ‘hemiscan’ or ‘reflection’ analysis protocols can be used with horizontally offset positioning of the patient on the table. The composition of the arm or leg that is off the table is then estimated from the corresponding limb that is fully scanned.

Quality in scanning, analysis and interpretation are of the utmost importance to achieve accurate body composition results. Phantoms specifically designed for monitoring the calibration of DXA systems are now commercially available. These phantoms have been used for longitudinal calibration corrections and cross calibration between similar systems. However, none of the phantoms developed to date have been shown to be appropriate for cross calibration between systems of different makes and models.

E.1.3. Advances in quantitative computed tomography and magnetic resonance imaging

A 3-D imaging method is required if data are needed on the composition or volume of an organ independent of the surrounding tissue. Computed tomography and MRI are common clinically available methods that can isolate organs such as individual muscles, the heart, brain, liver, etc. Organs are isolated, slice by slice through the body, from surrounding tissues. The primary limitations of MRI and CT are limited accessibility in low resource areas, high cost relative to other methods, and, in the case of CT, significant patient dose. However, full bore clinical systems can scan any part of the body and accommodate a wide variety of body sizes. Fat and muscle tissue quantification can be performed using several techniques including absorptiometry (CT), saturation mode (MRI), or tissue segmentation (CT and MRI).

Computed tomography is the leading technique for the study of specific localized fat deposits. Its most common research application for body composition assessment is to quantify subcutaneous, visceral and liver fat. The accuracy of CT to predict visceral and total abdominal fat is very good. The reproducibility of the technique is also excellent, with <1% variability between repeated measurements.

In adult studies, CT is the preferred technique for reasons of speed, availability and ease of protocol execution and scan analysis. Computed tomography is also calibrated to absolute standards of attenuation. Magnetic resonance imaging is the preferred method for research in children and adolescents where dose considerations are important [E.9]. Sophisticated algorithms for automated segmentation analysis of whole body MRI scans have recently been demonstrated [E.10] and were introduced by several companies. An example is shown in Fig. E.2. The MRI scan in this figure was acquired in less than 10 minutes using a three point Dixon (fat and water separated) scan protocol and shows colourized segmentation of all major muscle groups, visceral

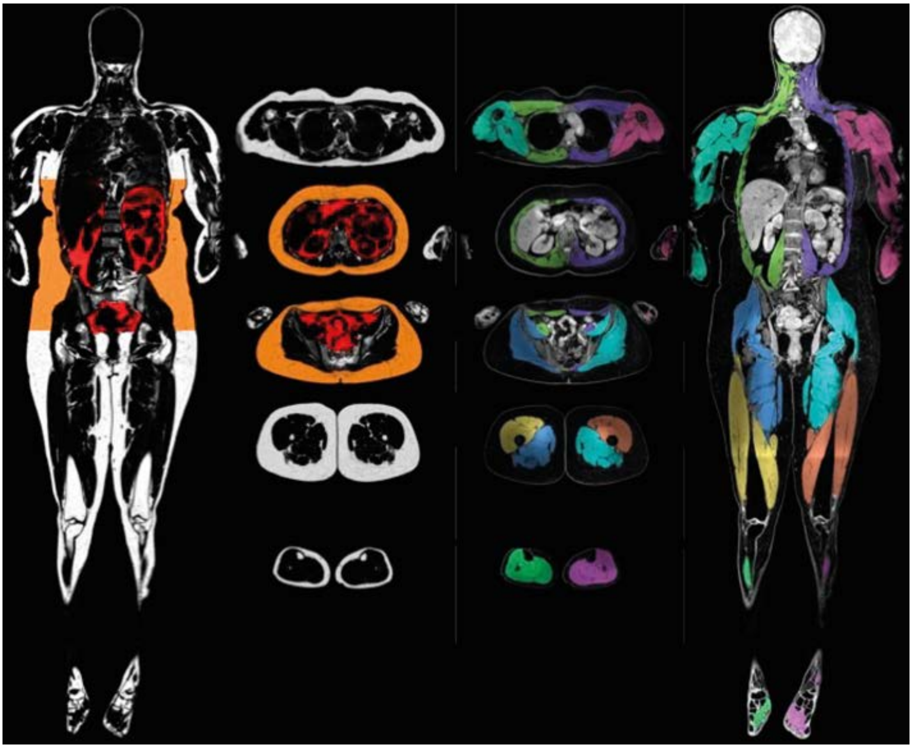


FIG. E.2. Example of automated segmentation of an MRI image using fat only (left) and water only (right) MRI images. Abdominal SAT and VAT are labelled, respectively, in orange and red and are overlaid onto the fat only image. Ten major muscle groups in different colours are overlaid onto the water only image. The segmentation was performed automatically. The whole body image took six minutes to acquire. (Images courtesy of O.D. Leinhard, Linköping University.)

fat and subcutaneous fat. It allows for reporting of organ volumes, water mass and fat mass.

E.1.4. Emerging technologies: Two and three dimensional whole body surface scanning

Body shape has long been used as a health indicator. Waist circumference and waist to hip ratio are widely used for this purpose. Furthermore, high muscularity or adiposity is readily apparent to even the casual observer. Recently, 2-D and 3-D whole body surface scanning systems have been proposed as novel platforms for body composition assessment. High accessibility, low cost and rich regional data make these modalities compelling options for the assessment of regional body composition.

Two dimensional body shape measures are acquired using a standard digital camera. It has recently been demonstrated how fat mass index and fat-free mass index can be derived from simple whole body silhouettes [E.11]. Such silhouette images can be easily captured using conventional cameras such as those found in mobile phones, making 2-D optical body composition measures highly suited for a variety of field applications. Three dimensional surface scanners and accompanying scan processing algorithms offer a rapid, non-invasive and scalable solution for body shape measurement. Measurements acquired using 3-D surface scanners have been shown to be highly precise. Current scan algorithms can automatically derive over 400 length, area and volume measurements from a whole body scan.

It was recently shown that regional volume and length measures derived using an eight-camera structured illumination 3-D surface scanner can be used to accurately predict DXA derived body composition measurements [E.12]. An example of matched DXA and 3-D surface scans is shown in Fig. E.3. Various

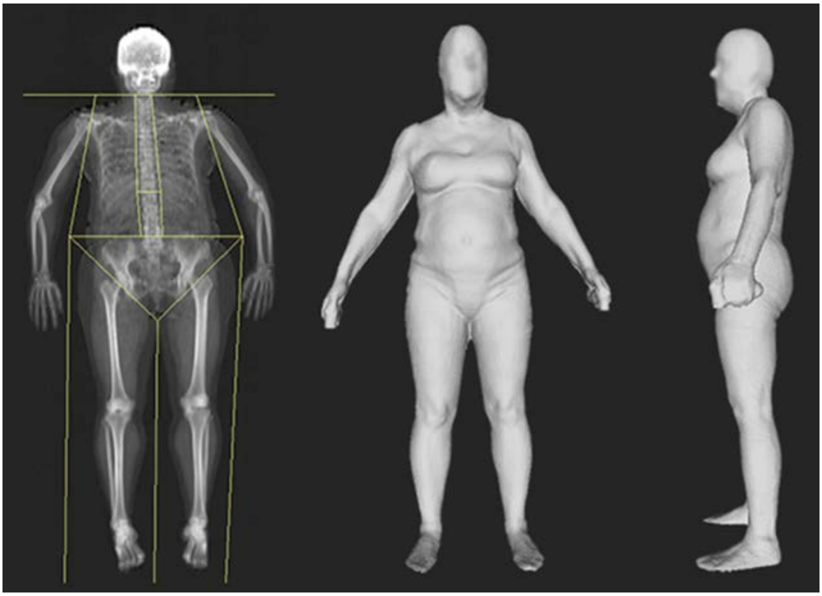


FIG. E.3. Matched whole body DXA scan (left) with 3-D optical surface scan, shown in coronal (middle) and sagittal (right) views. Body shape measurements derived from 3-D surface scans, such as torso width and depth, as well as leg and trunk regional volumes, can be used to accurately estimate DXA derived fat and lean body composition. (Image courtesy of J.A. Shepherd, University of California.)

3-D regional body volumes and depth measurements were used to predict fat mass and body fat percentage in the whole body (R^2 = 0.95 and 0.89, respectively), as well as in the android, gynoid, trunk and leg subregions. However, more validation against reference methods (DXA and isotope dilution) is needed.

In addition to accurate body composition estimates, 3-D body surface scanners can be used to acquire several other clinically relevant measurements. These include direct measurements such as waist circumference, as well as simple derived indices such as waist to hip ratio and waist to height ratio. These scanners offer the most accessible method of direct body surface area measurement. Similarly, this method is the most convenient tool for regional volume measurement, which can be used to calculate the trunk to leg volume ratio — a measure shown to be a significant risk factor for diabetes, hypertension, metabolic syndrome and mortality [E.13].

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F. THE INTEGRATED USE OF RADIATION, GENETIC AND SYMBIONT BASED METHODS TO MANAGE MOSQUITO DISEASE VECTORS

F.1. Mosquitoes and mosquito-borne diseases

Mosquito-borne diseases are a global threat to human health and well-being. Mosquitoes of the genus *Anopheles* (Fig. F.1) transmit malaria, which causes more than 600 000 deaths a year, while the Aedine mosquitoes *Aedes aegypti* and *Aedes albopictus* transmit diseases such as dengue, chikungunya, Zika and West Nile, among others, which are a threat to over 2.5 billion people in more than 100 countries [F.1]. Many diseases transmitted by mosquitoes have in recent years been spreading into previously unaffected areas, particularly those transmitted by the highly invasive *Aedes albopictus*.

FIG. F.1. Blood feeding female Anopheles arabiensis *mosquito.*

The management of viral diseases transmitted by mosquitoes, also called arboviruses, is complex. In most cases no specific treatments or vaccines are available. No vaccine is yet available for chikungunya, dengue, or the newly emerged Zika virus and the use of antiviral drugs is not very effective. Control of the mosquito vectors is therefore essential to reduce the disease burden, which is currently attempted mainly through the application of insecticide treated materials, indoor residual spraying, and the use of larvicides.

As acknowledged by the World Health Organization, additional methods of mosquito control are urgently needed, since the gains made in this area so far are endangered by unstable resource availability, growing resistance to the available tools, and changes in the behaviour of mosquito vectors, all of which make them harder to target. One promising additional method is the SIT, which can be integrated with other control tactics to effectively suppress mosquito populations [F.2].

F.2. The sterile insect technique as a tool to control mosquito populations

F.2.1. Developing the sterile insect technique for use against mosquitoes

In the last decade, much progress has been made in the development of the 'SIT package' for four disease transmitting mosquitoes (*Anopheles arabiensis*, *Anopheles gambiae*, *Aedes aegypti* and *Aedes albopictus*). The package includes mass rearing equipment, artificial diets, sterilization methods using both gamma and X rays, quality control methods and standard operational procedures (SOPs) to conduct feasibility studies on the use of the SIT to manage mosquito populations. A universal larval diet, suitable for *Anopheles* and *Aedes* mosquitoes and composed of ingredients that are widely and readily available, is now available [F.3, F.4]. Using this liquid larval diet and the associated SOPs, *Anopheles* and *Aedes* larvae can be mass reared efficiently in large trays fitted into a novel tilting rack system [F.5, F.6] (Fig. F.2). The cages are designed for easy blood feeding, sugar delivery, collection of eggs and cleaning [F.7]. In addition to the 10% sugar source provided *ad libitum*, a modified Hemotek membrane feeder is used to offer blood meals to female mosquitoes and water on the cage floor for oviposition [F.8]. Eggs are collected by flushing the bottom of the cage, and they are then dried and reliably quantified so that a predictable larval density can be achieved in rearing trays for the next production cycle (Fig. F.3). Male mosquitoes can be sterilized as late pupae, prior to emergence and release, using gamma or X ray irradiators (Fig. F.4). Dose response curves have been developed for one of the most important target mosquito species, *Anopheles arabiensis* [F.9, F.10], to select the optimal dose that provides adequate sterility, but also allows the males to efficiently compete with wild males.

As male mosquitoes are exposed to the stress of several processes, including mass rearing, sterilization, transport and release, ensuring good insect quality is a major concern. In addition to the quality control parameters recorded during the production phase, competitiveness studies are carried out under semi-field conditions to assess insect quality. Field cages simulate semi-field conditions and offer a good surrogate for the natural environment to carry out such experiments, as well as behavioural studies, including swarming investigations and mating compatibility. The field cages have been used to test the effect of various sterile to wild male ratios and the age of the sterile males on their mating

FIG. F.2. Liquid larval diet, trays and rack developed for the mass rearing of mosquitoes at the larval stage.

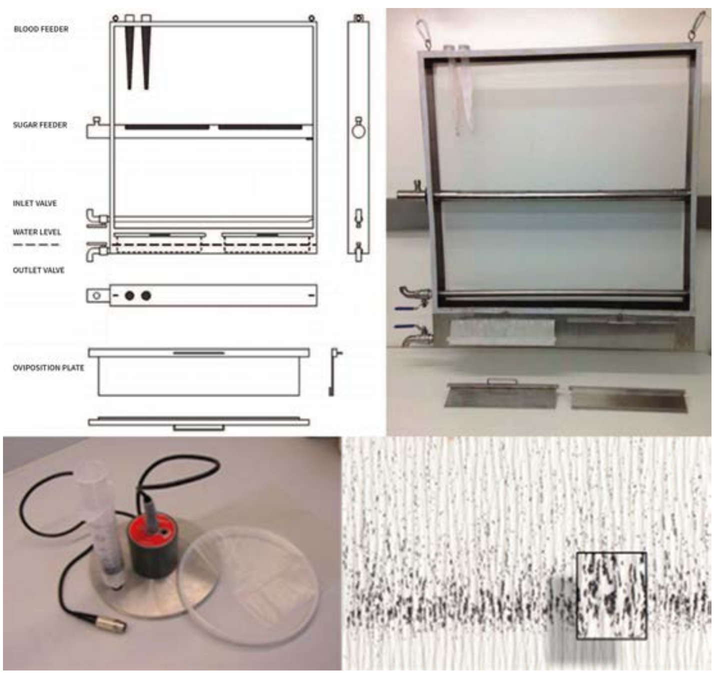

FIG. F.3. Adult mass rearing cage for Aedes *mosquitoes, blood feeding device and eggs collected on filter paper.*

FIG. F.4. Gamma ray (left) or X ray (right) irradiators are used for sterilization of male mosquitoes.

success. Preliminary data obtained for *Anopheles arabiensis* from the Sudan, *Anopheles gambiae* from Burkina Faso, and *Aedes albopictus* from China and Italy have been instrumental to improve the production processes and thereby the competitiveness of the sterile males, which is a crucial factor for a successful area wide integrated pest management programme that includes an SIT component.

F.2.2. Further technological requirements

In the case of the SIT for mosquitoes, as with other biologically based approaches, it is paramount only to release male mosquitoes as female mosquitoes are the vectors of disease, while male mosquitoes do not bite humans for blood and hence do not transmit the disease. Sex separation to eliminate females from the production line is possible on a small scale using the sexual dimorphism of *Aedes* mosquitoes [F.11, F.12] or spiking blood meals with chemicals such as ivermectin that are toxic for female *Anopheles arabiensis* [F.13]. The main challenge that needs to be addressed is the development of effective and robust genetic sexing strains for easy and safe elimination of the female mosquitoes at a mass rearing scale [F.14]. An *Anopheles arabiensis* genetic sexing strain that was based on an insecticide resistant mutation (dieldrin treatment would kill all the susceptible female mosquitoes but not the resistant male mosquitoes) has been available for several years and its potential use for field releases was recently assessed. The strain showed low productivity and genetic instability, and the adult males, which had hatched from eggs treated with dieldrin, were found to have small amounts of insecticide residues. Therefore, this strain has not been recommended for large scale operational applications [F.15]. Efforts are now ongoing to identify new morphological or conditional lethal markers for *Anopheles arabiensis* and also for *Aedes albopictus* and *Aedes aegypti* in order to develop effective genetic sexing strains.

In addition to the mosquito SIT package being developed, the technologies must be upscaled for application on an operational level. Large scale use of the SIT against other insect pests continues to reveal areas where new technologies could further improve efficiency and thus lead to more successful insect control programmes. Key issues to be resolved are handling, transport to the target area and actual release of sterile males, which must all be achieved without causing significant impact to their survival or post-release mating performance.

F.3. Complementary methods and their integration with the sterile insect technique to control mosquito populations

F.3.1. Complementary genetic approaches to mosquito control

In addition to the SIT, several other approaches have been developed for the management of mosquito vector populations. These technological platforms can be broadly classified into two groups. The first group includes self-limiting approaches, which are defined as methods whose effect cannot persist in the environment over time. Continuous releases are therefore required to achieve the desired population suppression effect. All population suppression methods such as the SIT, the release of insects carrying a dominant lethal (RIDL) transgenic approach and the symbiont based IIT are examples of self-limiting approaches. The second group includes self-sustaining approaches, which are defined as invasive methods whose effect can persist in the environment over time through positive selection. This could be used to replace a target mosquito population with one which was unable to transmit disease. Different methods have been suggested to achieve this, using transgenic technologies or using symbiotic bacteria.

The transgenic RIDL approach is based on the use of a genetic system carrying a lethal gene [F.16]. Homozygous strains carrying the RIDL system can be reared in the laboratory only in the presence of a repressor, which is usually the antibiotic tetracycline. Absence of this repressor kills the progeny. The *Aedes aegypti* strain OX513A carrying this genetic cassette has been evaluated in suppression trials on Grand Cayman Island and in Brazil and Panama. Both the male and female progeny from mating between the released OX513A males and wild females inherit one copy of the lethal genetic cassette and die in the early pupal stage. The suppression trials, which used sequential releases of transgenic males, were carried out on a small scale and the suppression levels reportedly reached, on average, 70–80% [F.17, F.18]. Problems associated with this approach include the lack of an efficient and robust sexing system, which is absolutely required in order to eliminate the chance of releasing pathogen transmitting females, the possibility of the evolution of resistance under mass rearing conditions as well as issues related with intellectual property rights, negative public perception in some areas and regulatory approval.

F.3.2. Symbiont based approaches

The other two methods, the IIT and the population replacement approach, are based on *Wolbachia,* which is a genus of maternally inherited symbiotic bacteria. It has been associated with the induction of several reproductive abnormalities, the most common one being cytoplasmic incompatibility which, in its simplest form, is expressed as embryonic lethality in crosses between infected males and uninfected females [F.19].

This symbiont has been exploited as a tool to either suppress (IIT) or replace populations of major mosquito vector species. The population suppression IIT approach has been tested in small pilot trials against *Culex pipiens*, *Culex pipiens quinquefasciatus*, *Aedes polynesiensis* and *Aedes albopictus* [F.20, F.21]. The main problem of this approach is that it also requires a perfect sexing system, which is not currently available, in order to eliminate the risk of releasing fertile and pathogen transmitting females. Some *Wolbachia* strains are also capable of blocking the transmission of major human pathogens, including plasmodium, dengue and chikungunya [F.22]. Releases of a line of *Aedes aegypti* transinfected with the *Wolbachia* strain *w*Mel, which expresses strong cytoplasmic incompatibility and also provides protection against dengue, replaced uninfected populations near Cairns, Queensland, Australia. However, the *w*Mel infection has a negative effect on fecundity and larval production, and the infection frequency generally does not reach 100%, suggesting that *w*Mel-infected *Aedes aegypti* mosquitoes may not rapidly invade neighbouring populations [F.23]. Additional concerns about the sustainability and biosecurity of the population replacement strategy include the potential evolution of resistance or that the blocking of the pathogen may be partial or even absent in some symbiotic associations. Indeed, the *Wolbachia* infection may enhance infection with other pathogens, including arboviruses [F.24].

F.3.3. Further requirements for the successful application of genetic control methods

The large scale application of any population suppression programme (SIT, transgenic or symbiont based) critically depends on the availability of efficient and robust sex separation methods, since releases of females would pose a significant risk of pathogen transmission. In the absence of an efficient sex separation method, a safe and effective strategy would require a combination of the SIT and symbiont based approaches to control mosquito vector populations. The proof of concept for this combined approach was developed against the mosquito species *Aedes albopictus* [F.25, F.26].

Whichever method or combination of methods is most effective against a specific mosquito vector in a given region, governmental support and public engagement will be required to ensure operational success. This is likely to be a greater challenge in the case of transgenic approaches, where public opposition is often greater and more stringent regulatory approval is required, in contrast to those based on the use of symbionts. On the other hand, the SIT is accepted readily by local populations and requires no regulatory approval. There are also issues surrounding intellectual property in using transgenic strains and symbiont based approaches which must be overcome if such a technique is to be applied at an operational level. However, new methods will have to be championed, because it is certain that evolutionary forces will drive increasing resistance to conventional mosquito control methods, and, eventually, even to the new transgenic and *Wolbachia* based pathogen protection methods. In contrast, no resistance can be developed against the SIT approach because irradiation induces dominant lethal mutations to the target insect in a random manner. A dynamic population suppression approach, which integrates the SIT and other compatible tactics in an area-wide insect pest management programme, may be the only way to manage mosquito populations and, potentially, to control the many diseases they transmit.

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G. ISOTOPIC TECHNIQUES FOR EFFECTIVE SOIL CONSERVATION MEASURES

G.1. Combined use of fallout radionuclides and compound specific stable isotope techniques for effective soil conservation measures

Soil degradation caused by inappropriate farm management practices leads to a loss of fertile soil and poor crop yields, thus contributing to food insecurity. The loss of arable land and the sedimentation and pollution of streams and lakes is also a significant environmental, social and economic threat.

In September 2015, the Economics of Land Degradation Initiative launched a report at the 70th session of the United Nations General Assembly stating that ecosystem service losses from land degradation cost up to US $10.6 trillion each year and that 1.4 billion people worldwide are directly impacted by land degradation [G.1].

In order to encourage more sustainable use and management of agricultural resources there is an urgent need to obtain reliable quantitative data on the magnitude and spatial extent of soil redistribution (erosion/sedimentation), and to better understand the key factors driving erosion and sedimentation processes. This better understanding will help guide where to apply appropriate soil conservation measures to efficiently control soil losses caused by erosion, and thereby reduce the economic, social and environmental impacts.

G.1.1. Fallout radionuclides for quantifying rates of erosion and sedimentation

The use of FRNs such as caesium-137, originating from thermonuclear weapon tests in the 1950s–1960s, as well as of naturally occurring geogenic radioisotopes such as lead-210 and cosmogenic radioisotopes such as beryllium-7, can help in assessing soil erosion and quantifying the effectiveness of soil conservation strategies.

After deposition on land by precipitation, the FRNs are strongly bound to fine soil particles and therefore constitute very useful soil tracers, which can assist in establishing soil erosion and sedimentation rates, and can subsequently be used to evaluate the efficacy of soil conservation measures to control soil erosion and thus prevent the excessive sedimentation associated with soil erosion. Owing to their different origins and half-lives, lead-210 and caesium-137 can provide a sound basis for establishing the erosion history of soils at large catchment levels over long and medium term periods, respectively. With the inclusion of beryllium-7, FRNs also allow the evaluation of short term erosion losses (Table G.1 [G.2]). Although many studies have utilized only a single FRN, the

TABLE G.1. COMPARATIVE ADVANTAGES AND LIMITATIONS OF CAESIUM-137, LEAD-210 AND BERYLLIUM-7 FOR QUANTIFYING THE RATES OF SOIL REDISTRIBUTION AFTER EROSION AND/OR SEDIMENTATION PROCESSES

FRN	Origin	Energy (keV)	Time		Sampling	Scale	Detector	Measurement		Sediment dating
			$t_{1/2}$	Span				Lab	In situ	
^{137}Cs	Artificial human made	662	30.2 yr	50 yr (MT)	Simple	Plot to large watershed	Normal HPGe γ	Easy	Easy	Feasible
^{210}Pb	Natural geogenic	46	22.8 yr	100 yr (LT)	Simple	Plot to watershed	Broad energy range HPGe γ	More difficult	Limited and unreliable	Feasible
^{7}Be	Natural cosmogenic	477	53.3 d	≤ 6 m (ST)	Fine depth incremental	Local plot to field	Normal HPGe γ	Easy	Longer count time compared to ^{137}Cs	Feasible

Note: MT: medium term, LT: long term and ST: short term erosion assessment.

use of two or even three FRNs can provide more valuable information on erosion history by generating datasets for different timescales [G.3].

The increasing worldwide use of FRNs to quantify soil erosion and sedimentation rates for a wide range of agri-environments, from an individual field to watershed scale, has clearly demonstrated the validity and potential of these isotopic techniques [G.4].

G.1.2. Compound specific stable isotope techniques for determining sources of sediments

A recently developed forensic stable isotope technique based on the CSSI signatures of inherent soil organic biomarkers allows for the sources of sediments to be discriminated and apportioned. Thus, CSSI signatures from different land uses can be used to complement the information provided by FRN data.

This is possible because the majority of plant communities produce a range of organic compounds that leak into the soil from their roots and bind to the soil particles, thereby labelling a particular land use with their biomarkers. Although all plants produce similar biomarkers, the carbon-13 stable isotopic signature of those biomarkers usually differs for each plant species. The CSSI technique is based on the measurement of the carbon-13 stable isotopic signature of the straight chain (C14–C24) of the plant origin fatty acids in the soil. By linking the CSSI fingerprints of land use to the FRNs of the sediments in deposition zones, an accurate and powerful approach for determining sediment origins is available to researchers for identifying areas that are prone to soil erosion.

Compound specific stable isotope and FRN techniques are complementary methods for studying the redistribution and origin of land sediments. Fallout radionuclides provide information on soil redistribution magnitude within agricultural systems (or on sedimentation at their outlets), while the CSSI fingerprints provide information about the origin of those sediments.

Developing a better understanding on how to reduce soil erosion and subsequent sedimentation related agri-environmental problems is a key requirement for successfully combating soil degradation, and also for mitigating many of the expected impacts of climate change. Use of these integrated isotopic approaches could allow farming communities to adopt specific and effective mitigation measures, such as the use of minimum tillage, mulching, cover crops, terracing, contour cropping and building of small stone walls and fences, all of which can minimize losses of soil fertility, crop productivity and deterioration of water quality and sedimentation of dams (Figs G.1 and G.2).

FIG. G.1. Terraces and contour farming used to promote soil conservation on a tea plantation in Lam Dong Province, Viet Nam.

FIG. G.2. Sediment transportation by erosion from a catchment to a water dam in Sri Lanka.

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