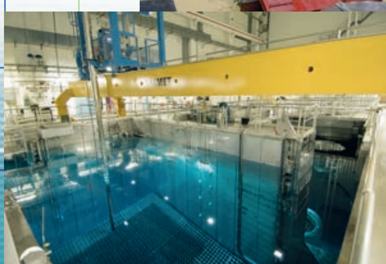
NUCLEAR TECHNOLOGY REVIEW

2014





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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

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EXECUTIVE SUMMARY

With 434 nuclear power reactors in operation worldwide at the end of 2013, nuclear energy had a global generating capacity of 371.7 GW(e). There were four new grid connections and ten construction starts on new reactors. Belarus became the second nuclear 'newcomer' State in three decades to start building its first nuclear power plant. Near and long term growth prospects remained centred in Asia, particularly in China. The 72 reactors under construction in 2013 represented the highest number since 1989. Of these, 48 were in Asia, as were 42 of the last 52 new reactors to have been connected to the grid since 2000.

Thirty States currently use nuclear power and about the same number are considering including it as part of their energy mix. Of the 30 States already operating nuclear power plants, 13 are either constructing new plants or actively completing previously suspended constructions, and 12 are planning to either construct new plants or to complete suspended constructions.

The IAEA Ministerial Conference on Nuclear Power in the 21st Century, held in June 2013, reaffirmed that nuclear power remains an important option for many States to improve energy security, reduce the impact of volatile fossil fuels prices and mitigate the effects of climate change. The Concluding Statement said that "nuclear power, as a stable base-load source of electricity in an era of ever increasing global energy demands, complements other energy sources including renewables." In the IAEA's 2013 projections, nuclear power is expected to grow by between 17% as the low projection and 94% as the high projection by 2030. These figures are slightly lower than projected in 2012, reflecting the continued impact of the Fukushima Daiichi accident, the low prices of natural gas and the increasing use of renewable energy. Additional information focuses on the linkages between nuclear power and climate change, as nuclear power, hydropower and wind energy have the lowest life cycle greenhouse gas (GHG) emissions among all the power generation sources.

The implementation of the IAEA Action Plan on Nuclear Safety remained at the core of the actions that were taken by Member States, the Secretariat and other relevant stakeholders to strengthen safety. Safety improvements continue to be made at nuclear power plants, including by applying lessons learned from the Fukushima Daiichi accident. This has contributed to strengthening the global nuclear safety framework. As sharing and transferring knowledge is critical for the safe and efficient management of any nuclear activity, additional information dedicated to nuclear knowledge management is available.

The continued enhancements and research in advanced fission reactors, such as water cooled reactors, fast reactors and gas cooled reactors, are expected to contribute towards more efficient use of nuclear fuel and reduce radioactive waste volumes. There is growing interest in small and medium sized reactors and in the use of nuclear power plants for non-electric applications such as desalination, process heat, district heating and hydrogen production.

Uranium spot prices remained at a seven year low, restricting companies from raising funds for exploration and feasibility studies, which will have an impact on future production. Although additional resources were reported in several States, many previously announced new projects are likely to be delayed.

Global uranium enrichment capacity continued its trend towards more energy efficient technologies. Gaseous diffusion plants were shut down in 2012 and 2013. Progress was made in centrifuge enrichment projects and laser enrichment has advanced towards commercialization.

Total fuel fabrication capacity has remained relatively constant, though it is expected to increase in the next few years to meet projected growth in demand.

With spent fuel and high level waste disposal facilities yet to begin operation, the amount of spent fuel in storage continues to increase. An additional 10 000 t HM (tonnes of heavy metal) of spent fuel were discharged from global fleet of nuclear power plants. This brings the total cumulative amount of spent fuel that has been discharged to approximately 370 500 t HM.

Disposal facilities for all categories of radioactive waste, except high level waste (HLW) and spent nuclear fuel (SNF) declared as waste, are operating worldwide. Licensing for the construction of geological disposal facilities in Finland, France and Sweden is under way. The research and development for HLW and SNF disposal are also progressing in other Member States.

There is considerable work to be done in the field of decommissioning. As of December 2013, 147 power reactors worldwide had been permanently shut down, more than 400 research reactors and critical assemblies, and several hundred other nuclear facilities, such as radioactive waste management or fuel cycle facilities, have been decommissioned or are undergoing dismantling. About 40% of all the operating nuclear power reactors are now more than 30 years old and about 7% of them are more than 40 years old. Although some may continue to operate for up to 60 years, many will be retired from service in the next 10 to 20 years.

In 2013, progress was made with cleanup activities in areas affected by the Fukushima Daiichi accident. Japan has allocated significant resources to planning and implementing remediation activities in large off-site contaminated areas. Particular efforts were devoted to enabling evacuated people to return to their homes. Good progress has also taken place in the coordination of remediation activities with reconstruction and revitalization efforts.

With International Thermonuclear Experimental Reactor (ITER) construction under way, the worldwide magnetic fusion programme is in a transition to one increasingly focused on the production of fusion energy on an industrial, power plant scale. Many States are independently developing programme plans and initiating new R&D activities leading to a demonstration of fusion energy's readiness for commercialization. Collectively, these plans and activities comprise a 'demonstration fusion power plant' (DEMO) programme, even though there is no single or coordinated view of the roadmap to the demonstration of electricity generation from fusion.

An increasing number of Member States are interested in developing research reactor programmes, some planning to use their first research reactor as the State's introduction to nuclear science and technology infrastructure. Three States are constructing new research reactors, while several have formal plans in place or are considering building new ones. Older reactors are being replaced by fewer, multipurpose ones and greater international cooperation will be required to ensure broad access to these facilities and their efficient use.

Operational challenges at processing facilities and older research reactors returned in 2013, albeit the ^{99}Mo supply was not as badly affected as it was between 2007 and 2010, owing to improved demand management and diversification in supply. Australia and South Africa continue to be the major suppliers of non-HEU ^{99}Mo. South Africa continued the conversion of its processes to the exclusive use of low enriched uranium (LEU). Belgium and the Netherlands continued their plans to convert their commercial scale production processes from high enriched uranium (HEU) to LEU.

The Czech Republic, Hungary and Viet Nam became HEU fuel free States after their spent HEU fuel was repatriated to the Russian Federation.

Nuclear technology continues to contribute significantly to the Millennium Development Goals. Many Member States are convinced that nuclear power would respond to climate change concerns by reducing carbon emissions. Non-power technologies make a significant contribution as well through programmes and technical cooperation in human health, food and agriculture, water resource management, the marine and terrestrial environment, radioisotope production and radiation technology. The safe and effective use of nuclear medicine and radiotherapy techniques are applied to combat a growing, global cancer epidemic that will disproportionately affect developing countries in the years to come. The eradication of poverty and hunger is supported by the IAEA's work in food and agriculture which uses nuclear technologies to improve the management of soils and land resources and to develop crop varieties that can grow in marginal or saline soils and under harsh conditions. Other technologies are used to improve livestock production and health, control insect pests that destroy crops and spread animal and human disease, and safely irradiate food products to protect consumers against the spread of food-borne illnesses and to reduce food spoilage.

Sustainable agricultural development is not possible without the sustainable management of water resources. Nuclear and isotope techniques are used to assess accurately the size, location and replenishment rate of water resources as well as to detect pollution in groundwater, which is vital information for the development of long term water resource management strategies. Environmental sustainability is supported by the use of nuclear science and applications in the detection and fate of radiopollutants in oceanic and coastal zones, the effects of these pollutants on marine organisms, and the assessment of key marine heat and carbon cycling processes and the impacts of climate change. The use of radiation technologies in the treatment of industrial and wastewater effluent and sludge helps to conserve water resources and to improve soil conditions, which further support environmental sustainability. Several of these nuclear technologies are explored in greater depth in this Nuclear Technology Review.

As the human population continues to grow, so does the demand for sufficient food; in turn, the amount of GHGs generated increases along the food production chain, particularly in relation to livestock. Innovative nuclear and nuclear related technologies have a unique role to play in animal nutrition, health, reproduction and breeding, and thereby contribute to sustainable food security while mitigating climate change by reducing GHG emissions.

Several nuclear techniques are used to study the uptake and utilization of microbial protein, and to develop better fodder crops, with a view to improving feed conversion rates and energy utilization — thus, in combination with a set of good practices, such as improved pasture management, reducing GHGs. Animal productivity is increased through the use of ^{125}I labelled progesterone in radioimmunoassay to identify pregnant animals in dairy herds, which can then be applied to reduce the proportion of non-productive animals involved in breeding. Nuclear techniques also contribute to characterizing livestock genomes, which facilitates the identification of advantageous gene traits, such as those responsible for resistance to diseases or the ability to thrive under climate or nutritional stress.

The Programme of Action for Cancer Therapy (PACT), a flagship programme of the IAEA, was moved to the Technical Cooperation Department as of 2014 and upgraded to the status of a Division. This new initiative aims to further enhance the effectiveness and efficiency of programme delivery. PACT will focus on resource mobilization and fundraising for cancer control related activities; develop new and improve existing cancer control related products and services for Member States' needs, such as imPACT Review Missions, the Virtual University for Cancer Control and Regional Training Network (VUCCnet) and the PACT Model Demonstration Sites (PMDS); and establish and strengthen links to partners with an emphasis on the complementary nature of respective mandates, in particular the World Health Organization.

X ray imaging is one of the most powerful tools in medical practice, with a broad spectrum of diagnostic applications, including cancer detection and staging. Additionally, multiple imaging modalities are used to develop treatment plans in radiotherapy and nuclear techniques are applied to improve cancer management worldwide. In medical radiology, there is an ever increasing demand for shifting from conventional (film based) imaging to digital imaging. Despite the significant advantages of digital imaging, such as improved reliability and ease of use, there are challenges to transitioning from conventional radiology, such as high capital costs, including for human capital development. The overall challenge for developing countries is to find an appropriate methodology for their needs and circumstances to move effectively from conventional film processing and storage to digital acquisition and display.

The use of digital imaging technology in combination with teleradiology allows diagnoses to be made irrespective of the distance between the site where the image is acquired and the location of the practitioner. Therefore, teleradiology is an effective method to address the uneven geographical distribution and local shortages of imaging specialists. The increasing role of technology may help to alleviate human resource shortages, although this technology requires more robust communication networks, and new roles in technical infrastructure support will be necessary.

The continued urbanization and industrialization of societies across the world contributes to the contamination of freshwater supplies and the generation of municipal sewage sludge. The treatment of industrial and wastewater effluent and sludge using nuclear technologies, such as electron beam accelerators, can help to preserve water resources and protect animal life and public health, and to produce fertilizing biosolids to improve soil conditions. These techniques have successfully demonstrated their effectiveness in the treatment of industrial textile dye wastewater, and in the sanitization of sewage sludge to provide high quality biosolids for agricultural applications. As water shortages have intensified, worldwide interest in reusing water has increased. Radiation technologies, in combination with conventional treatment processes, are now being tested for the production of high quality water for indirect potable reuse and are expected to become the predominant treatment technologies in the near future.

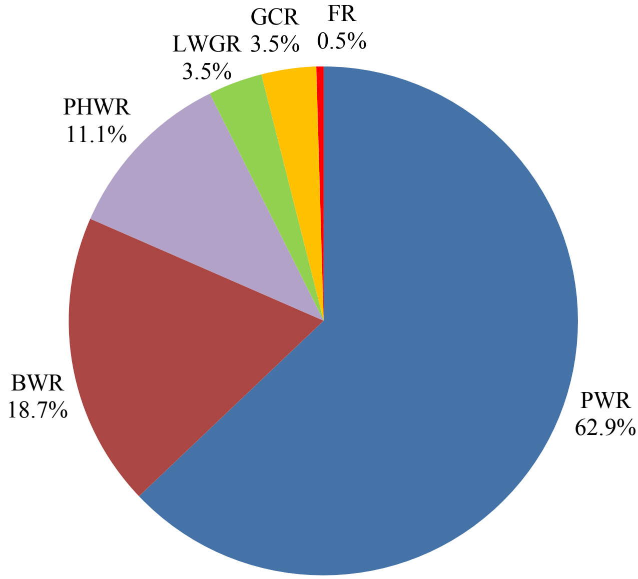
Marine ecosystems are a vital source of food and income for a large part of the world's population. In some regions, these ecosystems are periodically threatened by harmful algal blooms (HABs). Climate change, along with expanding economic activity, is expected to increase the frequency of these events. Algal toxins are responsible, for example, for massive economic losses to the shellfish industry through closures of harvesting facilities that are imposed when toxins in shellfish exceed regulatory levels. The frequency of HAB events is also increasing in freshwater environments, thereby posing a threat to freshwater aquatic species and livestock, as well as to humans. Nuclear techniques such as receptor binding assay (RBA) are proven tools for monitoring algal toxins in seafood and in the environment efficiently, as well as for studying the impact of climatic change on HABs and the marine ecosystem as a whole. RBA has a critical advantage over more conventional methods, as it is highly specific and very sensitive, therefore providing regulatory authorities and producers with an accurate early warning regarding HAB toxicity.

A. POWER APPLICATIONS

A.1. Nuclear power today

As of 31 December 2013, there were 434 nuclear power reactors in operation worldwide, with a total capacity of 371.7 GW(e)[1] (see Table A.1). This represents a slight decrease of 1.6 GW(e) in total capacity compared with 2012. There were four new grid connections in 2013: Hongyanhe 1 and 2 (1000 MW(e)) and Yangjiang-1 (1000 MW(e)) in China; and Kudankulam-1 (917 MW(e)) in India.

Of the commercial reactors in operation, approximately 81% are light water moderated and cooled reactors; 11% are heavy water moderated and cooled reactors; 3.5% are light water cooled, graphite moderated reactors; and 3.5% are gas cooled reactors (GCRs) (see Fig. A.1). Two reactors are liquid metal cooled fast reactors.



Note: BWR — boiling water reactor; FR — fast reactor; GCR — gas cooled reactor; LWGR — light water cooled, graphite moderated reactor; PHWR — pressurized heavy water reactor; PWR — pressurized water reactor.

FIG. A.1. Current distribution of reactor types.

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

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2013)[a]

State	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2013		Total operating experience up to the end of 2013	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Argentina	2	935	1	692	5.7	4.4	70	7
Armenia	1	375			2.2	29.2	39	8
Belarus			1	1 109				
Belgium	7	5 927			40.6	52.1	261	7
Brazil	2	1 884	1	1 245	13.8	2.8	45	3
Bulgaria	2	1 906			13.3	30.7	155	3
Canada	19	13 500			94.3	16	655	7
China	20	15 977	29	28 774	104.8	2.1	160	0
Czech Republic	6	3 884			29.0	35.9	134	10

For footnotes see p. 11

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2013)[a] (cont.)

State	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2013		Total operating experience up to the end of 2013	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Finland	4	2 752	1	1 600	22.7	33.3	139	4
France	58	63 130	1	1 630	405.9	73.3	1 932	3
Germany	9	12 068			92.1	15.4	799	1
Hungary	4	1 889			14.5	50.7	114	2
India	21	5 308	6	3 907	30.0	3.5	397	6
Iran, Islamic Republic of	1	915			3.9	1.5	2	4
Japan	48	42 388	2	1 325	13.9	1.7	1 646	4
Korea, Republic of	23	20 721	5	6 370	132.5	27.6	427	1
Mexico	2	1 330			11.4	4.6	43	11

For footnotes see p. 11

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State	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2013		Total operating experience up to the end of 2013	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Netherlands	1	482			2.7	2.8	69	0
Pakistan	3	690	2	630	4.4	4.4	58	8
Romania	2	1 300			10.7	19.8	23	11
Russian Federation	33	23 643	10	8 382	161.7	17.5	1 124	2
Slovakia	4	1 815	2	880	14.6	51.7	148	7
Slovenia	1	688			5.0	33.6	32	3
South Africa	2	1 860			13.6	5.7	58	3
Spain	7	7 121			54.3	19.7	301	1
Sweden	10	9 474			63.7	42.7	412	6

For footnotes see p. 11

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State	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2013		Total operating experience up to the end of 2013	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Switzerland	5	3 308			25.0	36.4	194	11
Ukraine	15	13 107	2	1 900	78.2	43.6	428	6
United Arab Emirates			2	2 690				
United Kingdom	16	9 243			64.1	18.3	1 527	7
United States of America	100	99 081	4	5 633	790.2	19.4	3 912	4
Total[b]	434	371 733	72	69 367	2 358.9		15 660	7

Source: Data are from the IAEA's Power Reactor Information System (PRIS), available at http://www.iaea.org/pris.

[a] The total figures include the following data from Taiwan, China:
- — Six units, 5032 MW(e), in operation;
- — Two units, 2600 MW(e), under construction;
- — 39.8 TW·h of nuclear electricity generation, representing 19.1% 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 (194 years, 1 month).

While the number of construction starts on new reactors dropped from sixteen in 2010 to four in 2011, seven constructions started in 2012 and ten in 2013 (see Fig. A.2), indicating an upward trend since the accident at the Fukushima Daiichi nuclear power plant. Construction work started on: Summer 2 and 3 and Vogtle 3 and 4, in the United States of America; Tianwan-4 and Yangjiang-5 and 6, in China; Shin-Hanul-2 (the new name for Shin-Ulchin-2), in the Republic of Korea; Barakah-2, in the United Arab Emirates; and Belarusian-1, in Belarus. After the United Arab Emirates, where construction of the first nuclear power plant started in 2012, Belarus is the second nuclear 'newcomer' State in three decades to start building its first nuclear power plant.

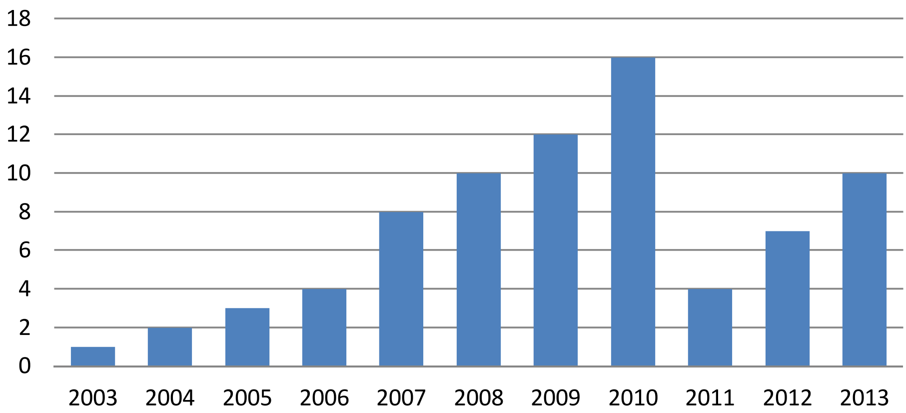
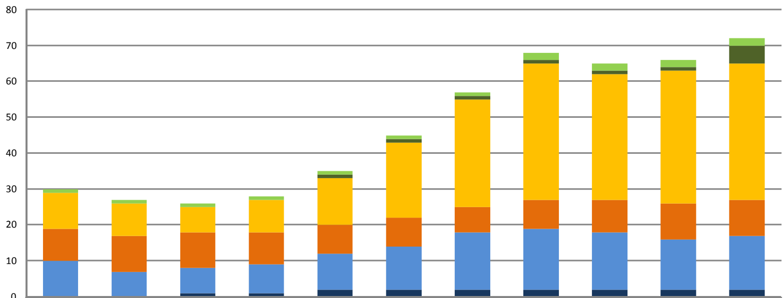


FIG. A.2. Trend of construction starts of power reactors.

In 2013, six reactors were officially declared permanently shut down: Crystal River-3, Kewaunee and San Onofre 2 and 3, in the United States of America; and Fukushima Daiichi 5 and 6, in Japan. This was three more reactors than in 2012 but much fewer than the 13 shutdowns in 2011. Additionally, one reactor in Spain, Santa Maria de Garona, was declared to be in long term shutdown status.

As of 31 December 2013, 72 reactors were under construction, the highest number since 1989. As in previous years, expansion as well as near and long term growth prospects remain centred in Asia (see Fig. A.3), particularly in China. Of these 72 reactors under construction, 48 are in Asia, as were 42 of the last 52 new reactors to have been connected to the grid since 2000.

In 2013, the trend of power uprates and of renewed or extended licences for operating reactors continued. The Canadian Nuclear Safety Commission has granted the six pressurized heavy water reactors (PHWRs) at Pickering a five



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

FIG. A.3. Number of reactors under construction by region.

year extension on their operating licences. The United States Nuclear Regulatory Commission (NRC) approved power uprates for three units, McGuire 1 and 2, and Monticello. The State Nuclear Regulatory Inspectorate of Ukraine granted a ten year operating licence extension of Unit 1 of the South Ukraine nuclear power plant.

In 2013, several States made significant progress towards their first nuclear power plant. The Emirates Nuclear Energy Corporation, in the United Arab Emirates, poured the first concrete of its second unit at the Barakah site in May 2013. The review of the construction licence application for two additional units is in progress. The first of four units is scheduled to be operational by 2017, with the remainder expected to be operational by 2020.

Belarus poured the first concrete of its first unit, Belarusian-1, in November 2013 (see Fig. A.4). This is the first of the two WWER-1200 units to be constructed under the contract signed with the Russian Federation’s Atomstroyexport in July 2012.

Turkey continues to develop its nuclear power programme infrastructure and to prepare for the construction of four WWER-1200 units at Akkuyu. In 2013, the project company for the Akkuyu nuclear power plant filed an environmental impact assessment report for the project. Turkey signed a cooperation agreement with Japan for a second nuclear power plant at Sinop. The IAEA’s Integrated Nuclear Infrastructure Review (INIR) mission in November 2013 concluded that Turkey had made progress in developing its nuclear infrastructure and made recommendations for further actions (see Fig. A.5).

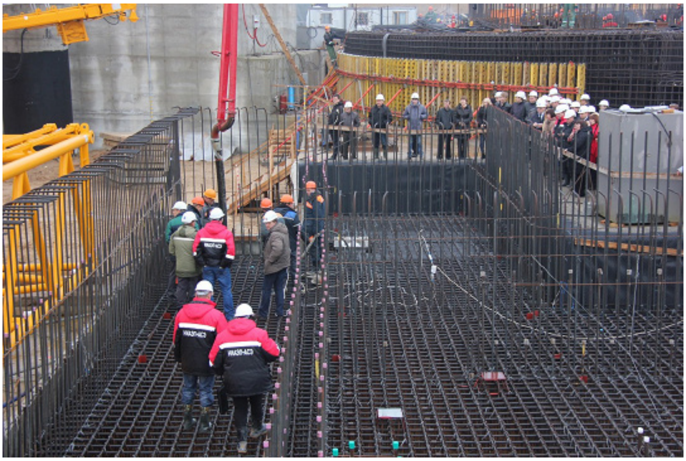


FIG. A.4. Construction of Belarus's first nuclear power plant started at the Ostrovets site on 6 November 2013 (courtesy of the Directorate for Nuclear Power Plant Construction, Belarus).

FIG. A.5. IAEA and international experts with Turkish counterparts during the INIR mission to Turkey, 4–14 November 2013 (courtesy of the Ministry of Energy and Natural Resources, Turkey).

Several States that have decided to introduce nuclear power are at advanced stages of infrastructure preparation. Following a 2011 intergovernmental agreement with the Russian Federation on cooperation for the construction of the two unit Rooppur nuclear power plant, Bangladesh started site preparatory work in 2013. In October 2013, Jordan selected the Russian Federation's

Atomstroyexport as a preferred vendor and is currently working on the characterization of the Amra site. Poland plans to build up to two nuclear power plants. An INIR mission in March 2013 concluded that Poland had made progress and made recommendations for further actions. In 2013, Viet Nam completed feasibility studies of two sites for nuclear power plants in Ninh Thuan with a total capacity of 4000 MW(e). Egypt and Nigeria continue to develop their infrastructure for introducing nuclear power. Jordan, Morocco and Nigeria officially requested INIR missions to be scheduled in 2014. In January 2013, South Africa became the first operating country to receive an INIR mission to review its nuclear infrastructure in preparation for planned, new construction.

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

Of the 30 States already operating nuclear power plants, 13 are either constructing new plants, including China, the Republic of Korea, the Russian Federation and the United States of America, or actively completing previously suspended constructions, including Argentina, Brazil and Slovakia. A further 12 operating States are actively planning to either construct new plants, including the Czech Republic, Hungary, South Africa and the United Kingdom, or to complete suspended constructions, such as Romania and the United States of America.

Although the nuclear industry has historically pursued economies of scale, there is growing interest in small and medium sized reactors (SMRs) — partly because they require smaller investments and reduce financial investment risks. Currently, 130 SMRs operate in 26 States, with a total capacity of 58.2 GW(e), and 14 of the 72 reactors under construction are SMRs. Approximately 45 innovative SMR concepts are at the research and development stage, which are covered in detail in Section B.1.4.

Producing electricity is the principal function of today’s operating reactors; a number of them are also currently used for desalination, process heat and district heating (see Fig. A.6). Additional possible future non-electric uses include hydrogen production: firstly, to upgrade low quality petroleum resources such as oil sands, while offsetting carbon emissions associated with steam methane reforming; secondly, to support large scale production of synthetic liquid fuels based on biomass, coal or other carbon sources; and thirdly, to serve directly as a vehicle fuel, most likely for light duty plug-in hybrid hydrogen fuel cell vehicles. The use of nuclear power plants for electricity generation and non-electric

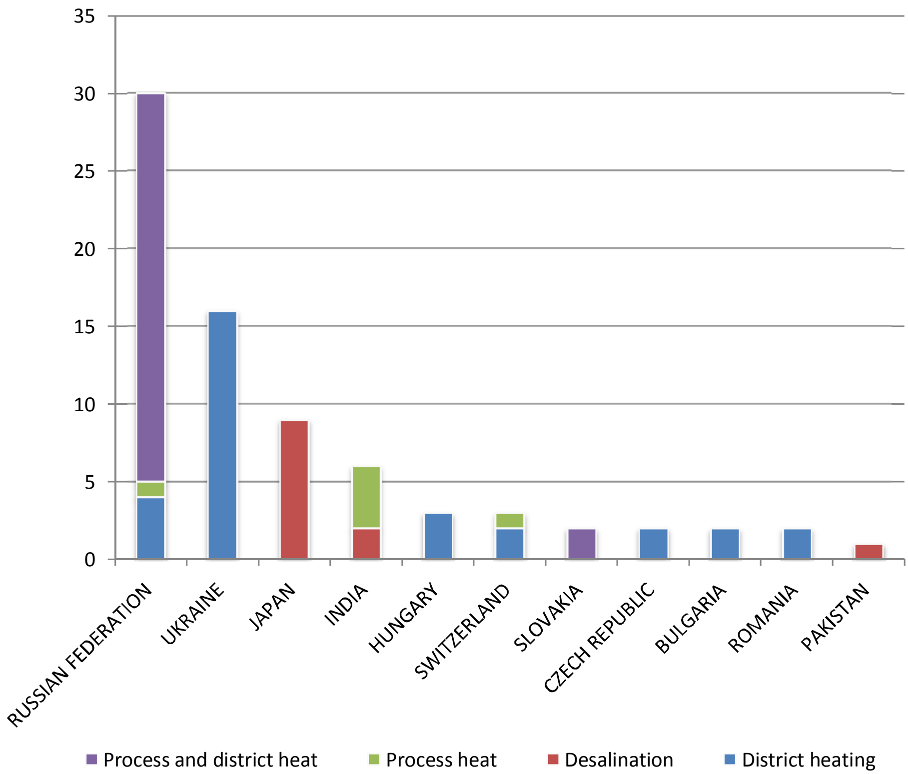


FIG. A.6. Number of reactors used for both non-electric purposes and electricity production.

applications (i.e. nuclear cogeneration) can offer a variety of economic benefits for large energy users, as higher efficiency in nuclear power plants translates into better economic performance, reduced emissions of all pollutants, increased reliability and power quality, better use of nuclear fuel and flexibility to the electric grid. Section B.1.6. is dedicated to nuclear cogeneration.

A.2. The projected growth of nuclear power

Thirty States have chosen nuclear power and about the same number again are considering including it as part of their energy mix, as they find its long term benefits attractive. One of the key messages that emerged from the IAEA Ministerial Conference on Nuclear Power in the 21st Century, which took place in St. Petersburg in June 2013, was that for many States, nuclear power would play an important role in achieving energy security and sustainable development goals. Nuclear power, as a clean low carbon source of energy, can help States to respond to increasing demands for electricity, limit carbon emissions in response to climate change concerns, reduce concerns regarding the security of energy supply and limit reliance on fossil fuels that are subject to regional price disparities and volatility.

Nuclear power: A low carbon technology

Nuclear power, hydropower and wind energy have the lowest life cycle greenhouse gas (GHG) emissions of all the power generation sources.[2] These technologies will become even more important as new carbon constraints are imposed in the next global climate change agreement due to be signed in 2015. Based primarily on the ecoinvent database and findings from the National Renewable Energy Laboratory, in the United States of America, the median value for GHG emissions from a light water reactor (LWR) is estimated at 14.9 g carbon dioxide equivalent (CO_2-eq) per kWh, including life cycle emissions from uranium mining to waste disposal.

Hydropower from alpine and non-alpine reservoirs, as well as run-of-the-river systems, has comparable life cycle GHG emissions to nuclear power. Wind emissions are dependent upon the size (class) of wind turbines, where smaller units (1–3 MW) actually produce lower emissions per capacity than larger units (>3 MW), which require higher use of energy and materials for construction. Small onshore and offshore units have comparable emissions to nuclear power, whereas the larger units can have ten times higher values.

To put these values in perspective, emissions from fossil energy are about ten times higher than for nuclear power. For example, hard coal is estimated at around 1200 g CO_2-eq per kWh and conventional natural gas is about half the value of coal, at approximately 650 g CO_2-eq per kWh. Fossil GHG emissions can potentially be reduced through the use of carbon capture and sequestration resulting in emissions for coal of about 200 g CO_2-eq per kWh and 150 g CO_2-eq per kWh for natural gas.

Although nuclear power already has inherently low GHG emissions, future emissions will be even lower, owing to more energy efficient production of enriched uranium, improved nuclear fuels and reactors that allow greater utilization, and extended lifetimes for nuclear power plants, which reduce the need to build new facilities.

[2] Annex I provides additional information on nuclear power and climate change.

In the IAEA's 2013 projections, nuclear power is expected to grow by between 17% as the low projection and 94% as the high projection by 2030. These figures are slightly lower than projected in 2012, and this is interpreted to reflect the continued impact of the Fukushima Daiichi accident, the low prices of natural gas and the increasing capacities of subsidized renewable energy.

In the high projection, the world total capacity would reach 722 GW(e) by 2030, nearly a doubling of capacity from 2012 levels. This estimate is based on optimistic but plausible assumptions on the rates of economic and electricity demand growth, particularly in the Far East. High case projection assumes that changes will be made to national policies on climate change and a strengthening of the global economy, leading to more States to introduce nuclear power in their energy mix or expand existing capacities.

In the low projection, the world total capacity for nuclear would grow to 435 GW(e) in 2030 — an increase of only 62 GW(e) from 2012 levels. This estimate assumes that current market, technology and resource trends will continue with few changes in laws, policies and regulations supporting increased adoption of nuclear power. The low projection reflects a prolonged pause or decision not to pursue nuclear development in some States due to the Fukushima Daiichi accident.

The strongest projected growth is in regions that already have operating nuclear power plants, led by Asian States, including China and the Republic of Korea. Eastern Europe, which includes the Russian Federation, as well as the Middle East and South Asia, which includes India and Pakistan, also show strong growth potential.

Other assessments also show nuclear growth comparable to the IAEA's projections. In World Energy Outlook 2013 [1], published by the International Energy Agency (IEA) and the Organisation of Economic Co-operation and Development (OECD), nuclear power is expected to grow to 513 GW(e) by 2030 under the Current Policies Scenario, 545 GW(e) in the New Policies Scenario and 692 GW(e) in the highest scenario, which limits the global increase in temperature to 2°C. This suggests that the IAEA's low projection is modestly conservative, with an estimate for 2030 that is 78 GW(e) lower than the IEA's lowest projection.

Figure A.7 compares the IAEA's 2013 projections, the IEA's 2013 scenarios and the 2013 projections by the World Nuclear Association (WNA) in The Global Nuclear Fuel Market: Supply and Demand 2013–2030 [2]. The high scenarios from the three organizations produce similar results.

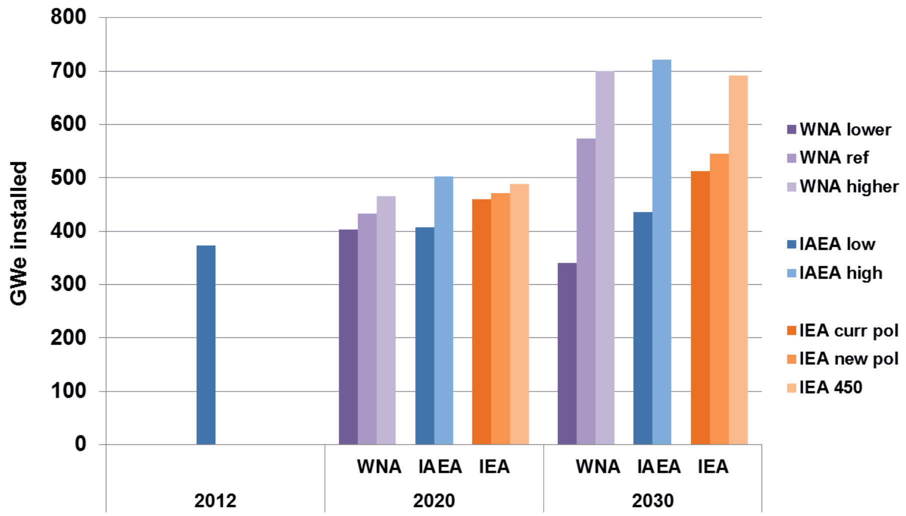


FIG. A.7. Comparison of nuclear power projections from the IAEA, the IEA and the WNA.

A.3. Fuel cycle

A.3.1. Uranium resources and production

Uranium spot prices remained depressed in 2013 at a seven year low, dropping from around US $115/kg U in the beginning of the year to approximately US $90/kg U by the close of the year (see Fig. A.8). The impact was also visible in the reported long term price, which was about US $150/kg U at the start of the year and dropped to about US $130/kg U at the end of the year. Reduced prices considerably restricted the ability of companies to raise funds for exploration and feasibility studies, which will have an impact on future production. Many previously announced new projects are likely to be delayed. Uranium 2011: Resources, Production and Demand [3], known as the Red Book and published jointly by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA) in 2012, estimated the total identified amount of conventional uranium resources, recoverable at a cost of less than US $260/kg U, at 7.1 million t U.

In 2013, additional resources were reported in many States, including Australia, Botswana, Canada, the Central African Republic, China, the Czech Republic, the Kingdom of Denmark (Greenland), India, Jordan, Mongolia, Namibia, the Russian Federation, Slovakia and South Africa.

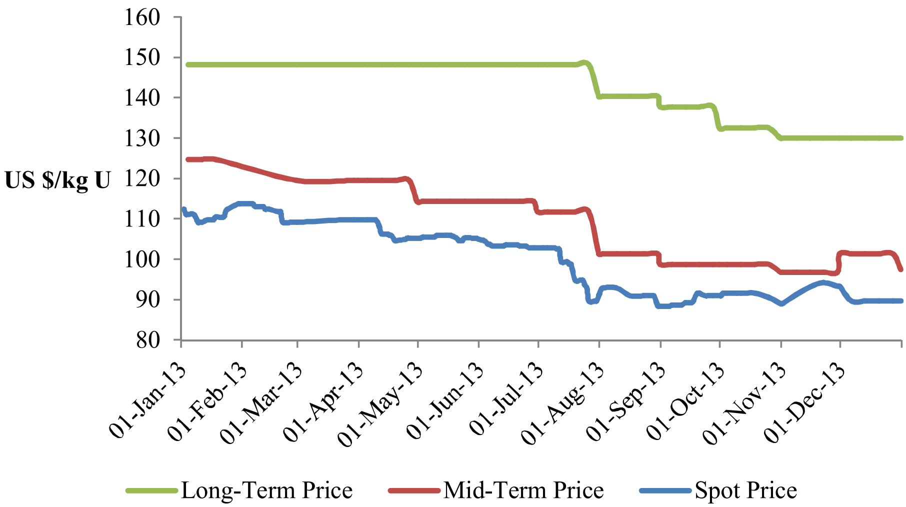


FIG. A.8. Uranium price trends, based on TradeTech uranium market indicators.

Preparations continued for the production of uranium as a by-product from the Talvivaara nickel mine, in eastern Finland. Uranium resources from this mine are 22 000 t U with an expected production of 350 t U per year. The extraction of uranium is forecast to start in 2014.

Seawater has been investigated as an unconventional source of uranium. Some 4.5 billion t U, representing an enormous energy resource, are dissolved in the world's oceans at very low concentrations of about 3.3 parts per billion, compared with terrestrial rock concentrations of 1000–5000 parts per billion. Some research continued into this potential source.

The WNA estimates that uranium production was 53 493 t U in 2011, 58 394 t U in 2012 and 54 039 t U in 2013.

In situ leaching (ISL) surpassed underground mining as the main production method in 2009, and the proportion of ISL production is expected to continue to increase in the medium term. In 2012, there were expansions at several ISL mines in Kazakhstan, which have increased production in the country by approximately 2250 t U annually. The WNA reports that ISL mining accounted for approximately 45% of world production for 2012.

In Namibia, the stage 3 expansion at Paladin Energy's Langer Heinrich mine was completed in 2012 to increase annual production to 2000 t U. A Stage 4 expansion to further increase annual production to 3900 t U is currently being studied. Because of current market conditions, AREVA kept on hold its development of the Trekkopje mine in Namibia. Construction has started on the Husab mine, in Namibia (see Fig. A.9), which is expected to start operation

FIG. A.9. Husab uranium mine site, Namibia (courtesy of the China General Nuclear Power Group).

by 2015, with full capacity of 5770 t U possible by 2017. A new mine in Niger, Imouraren, with a capacity of 5000 t U, is expected to start by 2015.

Feasibility studies are in progress for the Letlhakane project in Botswana. The first uranium mine licence for the United Republic of Tanzania was announced in April 2013, but the project is expected to be delayed owing to the depressed uranium markets.

In South Australia, Quasar Resources announced that it will commence ISL mining operations at the Four Mile East and West deposits in 2014. In Western Australia, Toro Energy's Wiluna uranium mine received the Federal Government's final environmental approval for its original deposits, and the company purchased the nearby Lake Maitland Uranium Project from Mega Uranium.

In the United States of America, the North Butte and Lost Creek ISL projects in Wyoming started production in May and August 2013, respectively.

In Turkey, pre-feasibility studies have been completed for the Temrezli ISL project and necessary licences have been granted for development. Production is now planned for 2016 with an annual amount of 350 t U.

In 2013, the parliament of Greenland (Kingdom of Denmark) voted in favour of lifting the long standing ban on the extraction of radioactive materials, including uranium. This move could enable the Kvanefjeld project, which is currently the subject of a feasibility study to evaluate a mining operation for the production of uranium, rare earth elements and zinc to proceed.

A preliminary metallurgical testing programme is being planned for the Närke project, in central Sweden, where alum shale could potentially host over 257 000 t U. In Spain, an environmental licence was issued for the Retortillo deposit within the Salamanca-1 uranium project and a formal process has been initiated for the issuance of a licence and permit for development. Romania announced plans to open a new uranium mine in Neamt to offset the depletion of resources in the current mine in Suceava.

Uzbekistan completed the construction of three uranium in situ recovery mining fields at Central Kyzylkum in 2013. China's Ministry of Land and Resources selected six uranium mines as national green mines. Green mines are environmentally friendly mining enterprises that pay attention to energy saving, emissions reduction and land reclamation in their daily operations. The Islamic Republic of Iran announced the start of operations at the Saghand uranium mine and the associated mill near Ardakan.

The WNA estimates that uranium production in 2013 covered only about 83% of the estimated uranium consumption in reactors of 64 978 t U. The remainder was covered by five secondary sources:

- Military stockpiles of natural uranium;
- Stockpiles of enriched uranium;
- Reprocessed uranium (RepU) from spent fuel;
- MOX fuel with ^{235}U partially replaced by plutonium from reprocessed spent fuel;
- Re-enrichment of depleted uranium tails.

At the estimated 2012 rate of consumption, the lifetime of 5.3 million t U, which are the estimated total resources economically viable at current market prices, would be 78 years.

Unconventional uranium resources and thorium further expand the resource base. Current estimates of potentially recoverable uranium as minor by-products are about 8 million t U. In March 2013, Uranium Equities, operating a demonstration plant in Florida, United States of America, announced that a study had found their PhosEnergy Process of extracting uranium from phosphates as viable and cost effective. An environmental impact assessment report was submitted for the Itataia mine in Santa Quitéria, Brazil, for two plants to produce phosphates and uranium concentrate.

Worldwide resources of thorium are estimated to be about 6–7 million t. Although thorium has been used as fuel on a demonstration basis, substantial work is still needed before it can be considered as such. There are a few rare earth element projects, which might produce thorium as a by-product and thorium containing residues, that are expected to go into production in the near term in Australia (Nolans Bore), Kingdom of Denmark (Kvanefjeld in Greenland) and South Africa (Steenkampskraal). In April 2013, Thor Energy commenced a thorium mixed oxide (MOX) fuel testing programme in Halden, Norway.

A.3.2. Conversion, enrichment and fuel fabrication

Six States (Canada, China, France, Russian Federation, United Kingdom and United States of America) operate commercial scale plants for the conversion of triuranium octaoxide to uranium hexafluoride (UF_6), and small conversion facilities are in operation in Argentina, Brazil, the Islamic Republic of Iran, Japan and Pakistan. A dry fluoride volatility process is used in the United States of America, while all other converters use a wet process. Total world annual conversion capacity has remained constant at around 76 000 t U as UF_6 per year. However, major changes are expected with a new plant being built in France (AREVA's Comurhex II) and another being refurbished in the United States of America (Honeywell Metropolis Works facility).

Comurhex II, with a capacity of 15 000 t U and a possible extension to 21 000 t U, will replace existing plants located at the Malvési and Tricastin sites. Comurhex II production will start progressively after the end of Comurhex I production.

The Honeywell Metropolis Works facility resumed production in June 2013 following equipment and process upgrades to improve efficiency and reduce plant downtime (see Fig. A.10).

FIG. A.10. New hydrogen fluoride vaporizer, Honeywell Metropolis Works facility, Illinois, United States of America (courtesy of Converdyn).

In 2011, the Russian Federation's State Atomic Energy Corporation "Rosatom" decided to start a project to concentrate all conversion facilities at one site, the Siberian Group of Chemical Enterprises in Seversk. The conversion site located in Angarsk is planned to be closed in April 2014.

Total current demand for conversion services (assuming an enrichment tails assay[3] of 0.25% ^{235}U) is in the range of 60 000–64 000 t per year.

Construction of a new uranium trioxide (UO_3) refinery in Kazakhstan, a joint venture between Kazatomprom and Cameco of Canada, is expected to start by 2018. Located in the Ulba Metallurgical Plant, in Ust-Kamenogorsk, its production capacity is expected to be 6000 t UO_3 per year.

Total global enrichment capacity is currently about 65 million separative work units (SWU) per year, compared with a total demand of approximately 49 million SWU per year. Commercial enrichment services are carried out by five companies: the China National Nuclear Corporation (CNNC), AREVA (France), Rosatom (Russian Federation), USEC and URENCO (both United States of America).

URENCO operates centrifuge plants in Germany, the Netherlands, the United Kingdom and the United States of America. URENCO's EU capacity totalled 14.7 million SWU per year as of the end of 2012. URENCO's facility in the United States of America is currently licensed to have an initial capacity of 3 million SWU per year, and the investment decision to expand to 5.7 million SWU was made in early 2013, with a target to reach this capacity by 2022 (see Fig. A.11). URENCO has requested a licence amendment from the NRC authorizing the company to increase its production capacity at URENCO USA to 10 million SWU per year.

USEC's Paducah gaseous diffusion enrichment plant, the world's oldest operating enrichment plant, reached the end of its commercial operations in 2013 after over sixty years of operation. USEC expects to continue operations at the site in 2014 in order to manage inventory, meet customer orders and meet the turn-over requirements of its lease with the United States Department of Energy (DOE).

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

FIG. A.11. URENCO enrichment facility, Eunice, New Mexico, United States of America (courtesy of URENCO).

Two new facilities using centrifuge enrichment are under design and development in the United States of America: AREVA's Eagle Rock Enrichment Facility and USEC's American Centrifuge Plant (ACP). The Eagle Rock Enrichment Facility is presently on hold and AREVA is seeking financial partners and alternative financial models to optimize capital expenditures. USEC's schedule for finishing construction of the ACP is dependent upon obtaining financing through DOE's loan guarantee programme.

The Global Laser Enrichment (GLE) facility in Wilmington, North Carolina, United States of America, completed in June 2013 the first phase of the test loop programme to demonstrate laser technology for uranium enrichment. Following the more detailed second phase studies, the first commercial facility is expected to be capable of producing 6 million SWU per year. According to Silex, the DOE has started talks with GLE on building another laser enrichment plant at the Paducah site to enrich its stockpiles (some 100 000 t) of high assay depleted uranium tails.

In France, AREVA officially launched its Georges Besse II North uranium enrichment facility in March 2013, in addition to its South plant inaugurated in December 2010.

In 2013, TVEL's Electrochemical Plant in Zelenogorsk, one of the four uranium enrichment plants operating in the Russian Federation, received a renewed licence to operate until 2023 (see Fig. A.12). In 2012, TVEL and Kazatomprom agreed to participate in raising the equity capital for the Ural Electrochemical Integrated Plant enrichment facility, which is planned to have a capacity of 5 million SWU per year.

FIG. A.12 . Electrochemical Plant in Zelenogorsk, Russian Federation (courtesy of TVEL).

There are also small enrichment facilities in Argentina, Brazil, India, the Islamic Republic of Iran, Japan and Pakistan. Argentina is rebuilding its gaseous diffusion capacity at Pilcaniyeu. Enrichment services are currently being imported from the United States of America.

Current total world deconversion[4] capacity in 2013 has remained at about 60 000 t UF_6 per year.

The current annual demand for LWR fuel fabrication services remained at about 7000 t of enriched uranium in fuel assemblies, but it is expected to increase to about 8000 t U per year by 2015. As for PHWRs, requirements accounted for 3000 t U per year. There are now several competing suppliers for most fuel types. Total global fuel fabrication capacity remained at about 13 500 t U per year (enriched uranium in fuel elements and fuel bundles) for LWR fuel and about 4000 t U per year (natural uranium in fuel elements and fuel bundles) for PHWR fuel. For natural uranium PHWR fuel, uranium is purified and converted to UO_2 in Argentina, Canada, China, India and Romania.

In China, production capacity for CNNC's fuel plant at Yibin was about 600 t U per year in 2012. As for the CNNC plant at Baotou, Inner Mongolia, which fabricates fuel assemblies for Qinshan's Canada deuterium–uranium reactor (CANDU) PHWRs (200 t U per year), its fuel capacity is being expanded

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

to 400 t U per year. A new plant is being set up in Baotou to fabricate fuel for China's AP1000 reactors.

A planned fuel fabrication facility in Kazakhstan is scheduled to be completed in 2014 as a joint venture by AREVA and Kazatomprom, and has an expected capacity of 1200 t U per year.

The construction of a WWER-1000 fuel fabrication plant, with a planned capacity of 400 t U per year, has continued near Smoline, Ukraine.

Over the past few years, TVEL has developed a fuel assembly for operation in pressurized water reactors (PWRs), and four pilot assemblies are to be loaded for test operation in Sweden's Ringhals-3 PWR plant in 2014.

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

India and the Russian Federation manufacture MOX fuel for use in fast reactors. In the Russian Federation, a MOX fuel manufacturing facility for the BN-800 fast reactor is under construction at Zheleznogorsk (Krasnoyarsk-26). The Russian Federation also has pilot facilities in Dimitrovgrad at the Research Institute of Atomic Reactors and in Ozersk at the Mayak Plant.

Worldwide, approximately 30 LWRs used MOX fuel in 2013.

In October 2013, AREVA's MELOX fuel fabrication facility began producing MOX fuel for the Borssele nuclear power plant in the Netherlands. In the past 30 years, 375 t of spent fuel from Borssele have been reprocessed in AREVA's La Hague plant.

A.3.2.1. Assurance of supply

In December 2010, the Board of Governors approved the establishment of an IAEA LEU bank in Kazakhstan. During 2012 and 2013, the IAEA Secretariat continued work on the financial, legal and technical arrangements and site assessments for establishing the bank. Pledges in excess of US $150 million for establishing it have been made by Member States, the European Union and the Nuclear Threat Initiative (NTI). By the end of 2013, pledges had been fully paid by Kuwait (US $10 million), Norway (US $5 million), the NTI (US $50 million), the United Arab Emirates (US $10 million) and the United States of America (approximately US $50 million); the European Union had paid €20 million of its pledged €25 million.[5]

A.3.3. Back end of the nuclear fuel cycle

Two different management strategies are used for spent nuclear fuel. The fuel is reprocessed to extract usable material (uranium and plutonium) for new fuel, or it is simply considered waste and is stored pending disposal. Currently, States such as China, France, India and the Russian Federation reprocess spent fuel, while other States, such as Canada, Finland and Sweden, have opted for direct disposal in a voluntary host community. Most States have not yet decided which strategy to adopt and are currently storing spent fuel and keeping abreast of developments associated with both alternatives.

Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste [5] legally binds EU Member States to establish and maintain a management policy. Attention in the spent fuel management area has also turned to demonstrating the behaviour of spent fuel in dry storage systems, as it is recognized that high level waste (HLW) repositories will not feature in many of the major nuclear power States for several decades.

Construction of a dry storage facility for used fuel from EDF Energy's Sizewell B nuclear power plant, United Kingdom, started in January 2013. The facility is expected to be operational by 2015.

Following its 2012 suspension of all final decisions on applications for new reactors or reactor licence renewals pending an update of its waste confidence decision and temporary storage rule, the NRC released in March 2013 the Waste Confidence Generic Environmental Impact Statement Scoping Process: Summary Report [6]. The draft generic environmental impact statement and proposed temporary storage rule was made available for public comment in 2013. While the Waste Confidence Directorate prepares the updated waste confidence decision and temporary storage rule, the NRC continues in parallel to review reactor applications, licence renewal applications and site specific independent spent fuel storage installation renewal applications.

In 2013, about 10 000 t HM were discharged as spent fuel from all nuclear power plants. The total cumulative amount of spent fuel that has been discharged globally up to December 2013 is approximately 370 500 t HM, of which about 253 700 t HM are stored in at-reactor or away-from-reactor storage

[5] Other assurance of supply mechanisms currently in place are described in the Nuclear Technology Review 2012 [4].

facilities. Less than one third of the cumulative amount of spent fuel discharged globally, about 112 800 t HM, has already been reprocessed. In 2013, the global commercial reprocessing capacity, spread across four States (France, India, Russian Federation and United Kingdom), was about 4800 t HM per year.

India continued constructing the Fast Reactor Fuel Cycle Facility at Kalpakkam in 2013. The proposed facility is designed to fabricate fuel for the upcoming prototype fast breeder reactor and the subsequent two additional units.

The Japan Nuclear Fuel Limited (JNFL) 800 t HM per year commercial reprocessing plant at Rokkasho, where the work was temporarily suspended as a consequence of the earthquake and tsunami on 11 March 2011, was ready for commissioning by the end of 2013. Trial production of vitrified waste at one of the two melting furnaces has been successfully completed. Once operational after receiving the regulatory clearances, the maximum reprocessing capacity of the plant will be 800 t per year (see Fig. A.13).

China has announced a proposal to reprocess used reactor fuel at a new plant, with a capacity to handle 800 t of spent fuel per year, to be built in cooperation with AREVA.

In October 2013, the UK Government announced an agreement with EDF which gives the go-ahead for the construction of the first nuclear power plant in the United Kingdom for 20 years. The 2008 Government white paper stated that the new build "should proceed on the basis that spent fuel will not be reprocessed" [7]. The current strategy for spent fuel management at Hinkley Point C will be storage at reactor for up to ten years followed by interim storage in an independent spent fuel storage facility until a geological disposal facility becomes available. The design basis for this storage facility is wet storage incorporating heat exchangers immersed in the pool with passive removal of thermal heat. This type of technology is also being assessed by Brazil.

FIG. A.13. Rokkasho Reprocessing Plant, Japan (courtesy of JNFL).

Between March and May 2013, the nine dry storage casks located at the cask custody area next to the sea at Fukushima Daiichi nuclear power plant were removed to the common spent fuel storage pool for inspection and subsequently relocated to the new temporary cask storage custody area. Inspections showed that neither cask containment nor fuel integrity was compromised. Further fuel recovery operations were started at the site in November 2013 with routine removals from the spent fuel pool of Unit 4, marking a significant milestone on the road to risk reduction and to decommissioning.

In October 2013, Japan's Recyclable-Fuel Storage Company, a subsidiary of Tokyo Electric Power Company and Japan Atomic Power Company, completed construction of the interim spent fuel storage building in the city of Mutsu, Aomori Prefecture. Its current licence provides for storage of 3000 t U of spent fuel, with a planned eventual capacity of 5000 t U. The final official test was witnessed by the Nuclear Regulation Authority (NRA). Further progress, however, is dependent on certification against new safety requirements from the NRA.

A.3.4. Decommissioning, remediation and radioactive waste management

Radioactive waste is produced from the use of nuclear technologies for energy production, research activities, medical and industrial applications. In addition to spent fuel declared as waste or the waste streams generated as a by-product of spent fuel reprocessing, radioactive waste arises during the operation of nuclear facilities, during their decommissioning and the associated remediation of sites, including legacy and current military use, and post-accident sites. The safe management of radioactive waste requires adequate management of waste streams, their treatment and conditioning, as well as providing adequate storage capacities, transport between facilities, and ultimately disposal.

A.3.4.1. Global radioactive waste inventory estimates

The global radioactive waste inventory reported as in storage in 2013 was approximately 68 million m^3 (see Table A.2). The cumulative amount of radioactive waste disposed of until 2012 was approximately 76 million m^3, which includes the deep well injection of some 29 million m^3 of liquid waste, and disposal of approximately 4000 m^3 of solid HLW, primarily from Chernobyl. The annual accumulation of processed HLW is fairly constant, at an average accumulation rate of approximately 850 m^3 per year worldwide (not including spent fuel).

TABLE A.2. ESTIMATE OF GLOBAL RADIOACTIVE WASTE INVENTORY FOR 2013

Waste class	Storage (m^3)[a]	Cumulative disposal (m^3)
Very low level waste (VLLW)	163 000[b]	193 000
Low level waste (LLW)	56 663 000[c]	64 992 000[d]
Intermediate level waste (ILW)	8 734 000	10 588 000
High level waste (HLW)	2 744 000	72 000[e]

Source: Net Enabled Waste Management Database (2013), official national reports and publicly available data.

Note: The figures in Table A.2 are estimates and are not an accurate account of radioactive waste quantities currently managed worldwide. In addition, there are inherent differences in the estimated storage quantities from year to year due to the following factors:

— Mass and volume changes during the waste management process;

— Changes in reporting and changes or corrections made by Member States to their own data;

— The addition of new Member States to the database.

[a] Wastes are typically treated and conditioned and taken through various handling steps during storage and prior to disposal. Therefore, the mass and volume of radioactive waste is continuously changing during the process of predisposal management. This can lead to discrepancies in estimated storage quantities from year to year.

[b] The estimate for VLLW is much lower than for LLW because many Member States with significant inventories of waste do not define a VLLW waste class. However, many of these Member States are currently re-evaluating their waste class definitions to better align them with the recommended classes in IAEA Safety Standards Series No. GSG-1, Classification of Radioactive Waste [8], and therefore this estimate will probably become larger in the future, with a corresponding drop in the LLW category.

[c] The estimate for LLW in storage does not include approximately 4×10^8 m^3 of liquid LLW reported as held in special reservoirs that are not isolated from the surrounding environment, because this does not meet the IAEA's definition of storage as described in the IAEA Safety Glossary [9]. For this reason, the status of this waste is still indeterminate with respect to inclusion in this estimate.

[d] The significant change in estimate of LLW and ILW cumulative disposal from the previous report is due to the inclusion of Russian Federation estimates.

[e] This volume of HLW is a combination of liquid disposal reported by the Russian Federation and approximately 4000 m^3 of solid radioactive waste reported by Ukraine that is considered temporarily disposed of until a more permanent design/location or solution is found. The Ukrainian HLW disposal was a result of the emergency cleanup of the accident at Unit 4 of the Chernobyl nuclear power plant.

As of December 2013, 467 storage facilities and 154 waste disposal facilities were in operation worldwide for the management of these waste inventories.[6]

A.3.4.2. Decommissioning

As of December 2013, 149 power reactors worldwide had been permanently shut down. In total, 16 power reactors have now been fully dismantled; a further 52 are in the process of being dismantled; 59 are being kept in a safe enclosure mode or are awaiting commencement of the final dismantling; 3 are entombed; and 17 do not yet have a specified decommissioning strategy. Approximately 40% of the 434 operating nuclear reactors worldwide are now more than 30 years old and about 7% of these are more than 40 years old. Although some may continue to operate for up to 60 years, many will be retired from service in the next 10 to 20 years. Except in special cases (e.g. graphite moderated reactors for which waste disposal routes are not yet in place), the generally preferred decommissioning strategy in most Member States is immediate dismantling — which means the radiological inventory is removed from the site and regulatory control is withdrawn within 15 to 25 years after shutdown.

Of the 480 research reactors and critical assemblies that have been shut down permanently, 70% have already been fully decommissioned. Several hundred other nuclear facilities, such as radioactive waste management or fuel cycle facilities have been decommissioned or are undergoing dismantling.

Member States with large nuclear power programmes (i.e. those that began nuclear energy production in the 1950s and 1960s) have made significant progress in dealing with the legacy from their early activities. These Member States have developed technologies and expertise for implementing decommissioning and environmental remediation programmes. This expertise is located in regulatory bodies, implementing organizations and a range of engineering organizations that provide supply chain services to the owners of the facilities and sites to be decommissioned or remediated. However, several decades of further effort are still needed for full remediation of major uranium production sites and sites used for early research activities. Examples of programmes where substantial progress with active decommissioning of nuclear power plants has been achieved during 2013 are:

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[6] Based on information provided by Member States to the IAEA's Net Enabled Waste Management Database at http://newmdb.iaea.org.

— France: Decontamination and removal of steam generators from the Chooz A nuclear power plant and their disposal at the French disposal site for VLLW at Morvilliers;
— Spain: Completion of segmentation and removal of reactor internals from the Jose Cabrera nuclear power plant;
— United Kingdom: Decontamination of spent fuel ponds at Bradwell nuclear power plant in preparation for entry into safe enclosure by 2015;
— United States of America: Ongoing removal of LLW from Zion nuclear power plant as part of a decision to implement immediate dismantling in place of the earlier strategy of deferred dismantling.

In Member States without major nuclear energy programmes, the level of progress is often much slower. The reasons for this include a lack of appropriate legal, policy and regulatory frameworks and associated funding schemes, a lack of appropriate technology and expertise, and inadequate mechanisms for engagement with affected stakeholders.

Japanese authorities have continued implementing the Mid-and-long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4, TEPCO (published in 2011, updated in June 2013) [10]. Phase 1 of the roadmap (December 2011–December 2013) focused on cleanup and stabilization work in preparation for removal of the fuel from the spent fuel pools (in Phase 2). Fuel removal from Unit 4 began in November 2013, one month ahead of the original schedule. Fuel removal from Unit 3 is scheduled for 2015 and from Units 1 and 2 for 2017. Plans are also being prepared for the removal in Phase 3 (after December 2021) of fuel debris from the reactor buildings. Depending on the seismic resistance of the damaged buildings, this may necessitate the construction of new superstructures on the buildings to be able to support the fuel handling machines. These issues will be addressed during 2014 and appropriate solutions proposed. Significant research and development work has continued to enable the development of remotely controlled devices to detect the damage to the primary containment vessels.

A.3.4.3. Remediation

Environmental remediation involves any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans. There are many sites all over the world in which remedial actions are being or still need to be applied. Remediation works generally involve enormous resources and demand appropriate planning, good project management, and qualified professionals, as well as an adequate regulatory framework. The impacts of these specific items in the implementation of both remediation and decommissioning projects is being analysed by the IAEA through the Constraints to Implementing Decommissioning and Environmental Remediation (CIDER) Project. Upon the conclusion of this project, it is expected that the IAEA will be able to provide a clear picture of why there has not been much progress in these activities and propose creative and innovative solutions.

A major development in 2013 is the progress achieved with cleanup activities in areas affected by the Fukushima Daiichi accident. Japanese authorities have allocated significant resources to develop strategies and plans and to implement remediation activities in large off-site contaminated areas. Particular efforts were devoted to enabling evacuated people to return to their homes. Good progress has also taken place in the coordination of remediation activities with reconstruction and revitalization efforts. An October 2013 IAEA follow-up mission assisted Japan in assessing the progress made since the previous mission in 2011, reviewed remediation strategies, plans and works, and shared its findings with the international community.

A.3.4.4. Legacy radioactive waste

The IAEA's Contact Expert Group for International Nuclear Legacy Initiatives in the Russian Federation (CEG) contributes to the successful implementation of international programmes in this area. The programme of dismantlement of decommissioned nuclear submarines is now nearing its completion. The defueled submarine reactor units are in the process of being sealed and placed in long term storage facilities. Currently, 65 submarine reactor units are placed at a storage facility in the north-west and three in the far east of the Russian Federation. A similar programme is being carried out in the United States of America, which has dismantled 114 nuclear submarines and ships. Two regional radioactive waste conditioning and storage centres are under construction in the north-west (see Fig. A.14) and far east of the Russian Federation. An international programme for recovering powerful radioisotope thermoelectric generators that were used at lighthouses along the coastline of the Russian Federation is also being successfully implemented.

A.3.4.5. Radioactive waste treatment and conditioning

Radioactive liquid wastes arise from most parts of the nuclear fuel cycle, including power reactors, reprocessing and waste treatment facilities, and decommissioning activities. Treatment techniques to reduce the radioactive contents include chemical precipitation, addition of finely divided radioactivity absorbers (both followed by solids removal), and the use of ion exchange

FIG. A.14. The construction of the Regional Centre for Radioactive Waste Conditioning and Long Term Storage in the north-west of the Russian Federation (courtesy of Energiewerke Nord GmbH).

absorbers in column form. Alternatively, evaporation or reverse osmosis (atomic level filtration) may be used. The characteristics of specialist ion exchanger absorbers continue to be improved by enhancing selectivity for key radionuclides and improving physical properties for column use, for instance by using composite materials. Liquid waste treatment has been a significant feature of the Fukushima Daiichi accident remediation through the use of an internationally supplied treatment facility. All of the processes mentioned above are combined to remove large amounts of the various radionuclides at Fukushima.

Waste conditioning includes the immobilization of radionuclides, placing the waste into containers and providing additional packaging. Common immobilization methods include solidifying low and intermediate level liquid radioactive waste using cement, bitumen or glass, and vitrifying high level liquid radioactive waste in a glass matrix or embedding it in a metal matrix. Current trends continue to improve the characteristics of low and intermediate level waste (LILW) immobilization processes. Egypt, India, the Russian Federation, Serbia and the United States of America have modified processes by admixtures to enhance cement's physical properties and tailor the immobilization potential for specific waste species or groups of species and counter the potentially harmful effect of inactive waste species. China, France, the Russian Federation, Switzerland, the United Kingdom and the United States of America have developed novel binders to overcome the limitations in the properties of Portland cement. France reported on the stabilization of soluble zinc salts using calcium sulphoaluminate cement (CSAC).

The IAEA has recently evaluated four types of novel cementitious materials [11]:

— CSAC;
— Calcium aluminate cement (CAC);
— Geopolymer made from alkali silicate and metakaolin (SIAL);
— Magnesium phosphate cement.

Recent favourable construction experience with geopolymer materials suggests that their more widespread application to waste conditioning is possible. SIAL geopolymers have demonstrated enhanced compressive strength and low leachability of ^{137}Cs, and are licensed for use in the Czech Republic and Slovakia for radioactive sludge and resin solidification. Research in Australia, the Russian Federation, Slovakia and the United Kingdom is likely to generate more knowledge, including information about their long term durability.

A.3.4.6. Radioactive waste storage

Waste storage enables appropriate containment and isolation of the waste, and facilitates its retrieval for further processing or disposal. Notable trends for radioactive waste storage have been observed during the past decade such as extended storage time and enhanced safety storage facilities. These have become more popular particularly for higher activity radioactive waste. A guide on good practices for regulating storage of radioactive waste is the UK Nuclear Decommissioning Authority’s Industry Guidance: Interim Storage of Higher Activity Waste Packages — Integrated Approach [12], published in 2012. The principles used include:

— Cradle to grave life cycles;
— Consistent waste package and storage conditions to minimize waste generation;
— Prevention is better than cure;
— Foresight in design;
— Effective knowledge management.

The guidance envisages that storage facilities should have the capability to last for at least 100 years.

For new stores, the design life should typically be at least 100 years. Moreover, if it is proposed to use an existing structure, modified as appropriate, as a store, it should be demonstrated that the structure meets modern construction standards, the materials chosen for any modification work are appropriate, and the resultant store is consistent with a design life target of at least 100 years.

A.3.4.7. Radioactive waste disposal

Disposal facilities for all categories of radioactive waste, except HLW or spent fuel, are operational worldwide. These include:

- Trench disposal for VLLW (e.g. in France, Spain and Sweden) or for LLW in arid areas (e.g. in Argentina, India, South Africa and United States of America);
- Near surface engineered facilities for LLW (e.g. in China, Czech Republic, France, India, Japan, Slovakia, Spain, Ukraine and United Kingdom);
- Subsurface engineered facilities for LILW (e.g. in Finland and Sweden);
- Borehole disposal of LLW carried out in the United States of America;
- Geological facilities to receive LILW (e.g. in Hungary and United States of America).

Disposal options for naturally occurring radioactive material waste vary according to national regulations and range from trench disposal facilities to subsurface engineered facilities (e.g. in Norway).

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

Canada is pursuing the development of two geological disposal facilities. The first, at the Bruce site facility for LLW and ILW from Ontario Power Generation, is currently in the licensing phase with public hearings having been completed in 2013 and a regulatory decision is expected in late 2014 or early 2015. The second is an undefined site for Canada’s Repository for Used Nuclear Fuel and Centre of Expertise. Working with 21 volunteer communities that expressed interest in learning about Canada’s plan for the safe, long term management of used nuclear fuel, the Nuclear Waste Management Organization completed a first phase of preliminary assessment with eight of these communities and is pursuing assessments with the remaining 13. Four of these initial eight communities were judged to be suitable to progress to the next phase of the assessment.

China followed its medium term plan to manage its LILW in five regional disposal sites by 2020 with a total disposal capacity of about 1 million m^3. Two of these are in operation with current capacities of 20 000 m^3 and 80 000 m^3. The third site is under construction and the remaining two sites are to be developed.

China currently foresees geological disposal needs deriving from 140 000 t of spent fuel from a fleet of 48 reactors. The corresponding HLW after reprocessing would need a disposal solution. Plans to progress towards geological disposal of HLW includes siting (2014), construction (2017) and operation of an underground research laboratory by 2020; performing in situ R&D and beginning the construction of a deep geological repository (DGR) by 2040; and for disposal operations to begin by 2050.

In Finland, Posiva hopes to receive a construction licence for its DGR by late 2014 or early 2015, and is preparing to carry out full scale demonstrations to resolve the remaining scientific and technical issues in order to obtain an operating licence. Posiva expects to begin operations in the early 2020s.

The French National Radioactive Waste Management Agency (Andra, Agence nationale pour la gestion des déchets radioactifs) is preparing the industrial phase of its reversible disposal Cigéo project for ILW and HLW, and has undertaken a feasibility review and a formalized public stakeholder engagement process prior to submitting a licence application. In 2013, plans for the Cigéo facility reached the stage of final public consultation, organized by the Commission nationale du débat public (the national commission for public debate). Initial plans for public meetings had to be replaced by on-line debates following a series of protests. A citizens' committee was established as part of this process and subsequently concluded 'a priori' for a non-opposition to the Cigéo project. Pending licence application submission in 2015 and granting of a construction licence in 2018, Andra plans on disposal commissioning by 2025.

Germany adopted a repository site selection act in June 2013. An independent commission will conduct the process for selecting the new repository site for heat generating waste. The previously considered exploration facility in Gorleben is not excluded from the new process.

Following an opening ceremony in December 2012, regular operations started at Hungary's Bátaapáti disposal facility, designed to receive 40 000 m^3 of LILW from nuclear power plant operations. The design allows for parallel construction of further disposal vaults while the waste is being placed in existing ones.

In the Republic of Korea, the construction of the Wolsong LILW Disposal Center (WLDC) is almost complete and the first phase of the WLDC, accommodating 100 000 drums, is to be completed in June 2014. The Government launched a commission to publicly discuss future management options for spent fuel. The KAERI Underground Research Tunnel will be expanded to accommodate the R&D programme foreseen in support of geological disposal.

Development of the Lithuanian near surface repository for LLW is currently in the detailed planning stage, while the VLLW repository is scheduled for construction to begin in the second half of 2014. Until disposal becomes available, waste packages are being emplaced to a 4000 m^3 buffer storage facility, which received a licence for operation from the State Nuclear Power Safety Inspectorate in May 2013.

The Polish Geological Institute has undertaken preparatory actions to re-initiate the development of a geological disposal programme. Preliminary site characterizations to select candidate sites for a near surface disposal facility will be followed by a local public and administrative consultation phase.

In the Russian Federation, design development is under way for the creation of an underground laboratory at the Nizhnekanskiy granitoid massif, at a depth of 500 m, in the Krasnoyarsk region, in Siberia, to study the possibility of disposal of long lived high and intermediate level waste. The planned capacity is for 7500 casks of heat generating waste and 155 000 m^3 of non-heat generating waste. A disposal facility for LLW and short lived ILW has been sited in the Leningrad region, in a clay formation at a depth of 60–70 m below the surface (see Fig. A.15). It is designed to receive 50 000 m^3 of LLW in vault type disposal chambers during the first phase of operations.

In Sweden, the licensing process for the spent fuel disposal facility is expected to last for several more years. In September 2013, the Swedish Nuclear Fuel and Waste Management Company (SKB, Svensk Kärnbränslehantering AB) submitted for review the latest research, development and demonstration programme for geological disposal in Sweden, and is currently preparing revised calculations for future costs of the spent fuel management programme. This will serve as a basis for the Government to decide on fees to be contributed to the Nuclear Waste Fund, from which this programme is being financed.

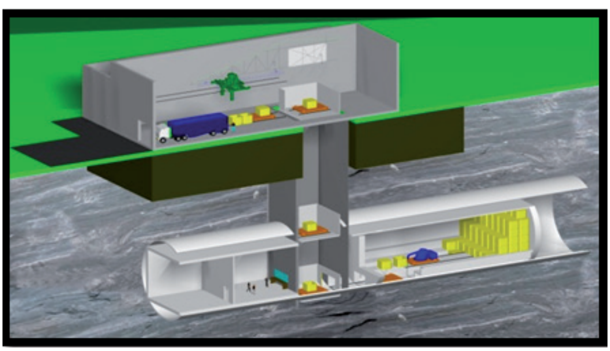

FIG. A.15. Concept of emplacement operations at the Russian Federation's planned LLW disposal facility (courtesy of the All-Russia Design and Research Institute for Integrated Power Technology).

Switzerland is currently revising its ordinance on the decommissioning and disposal funds. Proposals to amend future cost estimations include a reduction of the inflation rate (from 3% to 1.5%) and of the return on investment (from 5% to 3.5%) used for previous estimates, as well as adding a 30% ‘uncertainty allowance’. The Federal Government approved Nagra’s comprehensive waste management programme covering LILW and HLW. Proposals for the location of near surface facilities were made in 2013 and stage 2 of the sectorial plan process leading to the selection of at least two sites for LILW and HLW repository is ongoing.

Ukraine, in collaboration with the European Commission, is developing a national radioactive waste geological disposal plan and intends to perform preliminary safety assessments for three potential sites by 2017. The near surface LILW disposal facility at Buryakovka, developed following the Chernobyl accident, is undergoing a capacity expansion of 120 000 m^3 from its current capacity of approximately 700 000 m^3, under a European Commission funded reconstruction project.

The West Cumbria region, in the United Kingdom, withdrew from the geological disposal site selection process in January 2013. The UK Government maintains its emphasis on the development of geological disposal and seeks proposals on how to revise and improve the site selection process.

In the United States of America, Panel 7 at the DOE’s Waste Isolation Pilot Plant has received approval from the New Mexico Environment Department for disposing of defence sector waste materials which are contaminated with man made radioisotopes that are heavier than uranium. Building on the recommendations of the Blue Ribbon Commission on America’s Nuclear Future, the national strategy for HLW and spent fuel management foresees the development of pilot and larger interim storage facilities, as well as making demonstrable progress on siting and characterizing geological disposal sites. The NRC will continue to process the Yucca Mountain Project licence application.

A.3.4.8. Management of disused sealed radioactive sources

Disposal options for disused sealed radioactive sources (DSRSs), including co-disposal with other waste at suitable facilities, increased number of recycling and repatriation options, or disposal in dedicated boreholes, are under serious consideration in several States including Ghana, Malaysia, the Philippines and South Africa.

A number of successful operations were conducted in 2013 to remove DSRSs from user premises and bring them under control by moving them either to a national radioactive waste storage facility or to another institution with proper storage conditions. The mobile hot cell was deployed in the Philippines in April 2013 to condition 22 high activity DSRSs and place them into safe and secure storage. Five DSRSs in Bosnia and Herzegovina were recovered and removed from the country for recycling. The repatriation of disused French manufactured Category 1 and 2 sources was initiated in several Member States including Cameroon, Lebanon and Morocco. The repatriation of two such sources in Sudan was completed in 2013.

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

Various technical documents and training modules were produced and used to assist Member States to become technically proficient in the safe and secure conditioning of Category 3–5 DSRSs. Operations involving the conditioning of such sources were completed in Egypt and Morocco, and local and regional personnel were trained.

The IAEA extended access to the International Catalogue of Sealed Radioactive Sources and Devices to many individual State nominees and to international agencies such as Europol, thereby facilitating the identification of DSRSs found in the field.

The International Conference on the Safety and Security of Radioactive Sources: Maintaining the Continuous Global Control of Sources throughout Their Life Cycle, held in Abu Dhabi in October 2013, highlighted the fact that considerable challenges remain with the management and disposal of DSRSs, such as a lack of certified transport packages, long term storage facilities and end of life management guidance.

A.4. Safety

In 2013, safety improvements continued to be made at nuclear power plants throughout the world, including through the identification and application of the lessons learned so far from the Fukushima Daiichi accident. Significant progress has been made in several key areas, such as:

- Assessments of safety vulnerabilities of nuclear power plants;
- Improvements in emergency preparedness and response capabilities;
- Support to Member States planning to embark on a nuclear power programme;
- Strengthening and maintaining capacity building;
- Protecting people and the environment from ionizing radiation.

The progress made in these and other areas has contributed to the enhancement of the global nuclear safety framework.

The IAEA continues to share and disseminate the lessons learned from the Fukushima Daiichi accident. The IAEA Action Plan on Nuclear Safety, adopted by the General Conference after the Fukushima accident, remained at the core of the safety actions that were taken by Member States, the Secretariat and other relevant stakeholders. In 2013, the IAEA organized the International Experts' Meeting on Decommissioning and Remediation after a Nuclear Accident (28 January–1 February), the International Experts' Meeting on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant (21–24 May) and the International Conference on Effective Nuclear Regulatory Systems (8–12 April). In 2013, the IAEA published the IAEA Report on Decommissioning and Remediation after a Nuclear Accident [13], the IAEA Report on Strengthening Nuclear Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [14] and the IAEA Report on Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [15].

At the 56th regular session of the General Conference, the Director General announced that the IAEA will prepare a report on the Fukushima Daiichi accident to be finalized in 2014. The report will, among other things, cover the description and context of the accident, safety assessment, emergency preparedness and response, radiological consequences as well as post-accident recovery.

The operational safety of nuclear power plants remains high, as indicated by safety indicators collected by the IAEA and the World Association of Nuclear Operators. Figure A.16 shows the number of unplanned scrams per 7000 hours (approximately one year) of operation. This is commonly used as an indication of success in improving plant safety by reducing the number of undesirable and unplanned thermalhydraulic and reactivity transients requiring reactor scrams. As shown, steady improvements have been achieved in recent years. The increase from 2010 to 2011 is related to the high number of scrams triggered by the March 2011 earthquake in Japan.

Additional information on nuclear safety can be found in Nuclear Safety Review 2014 [16].

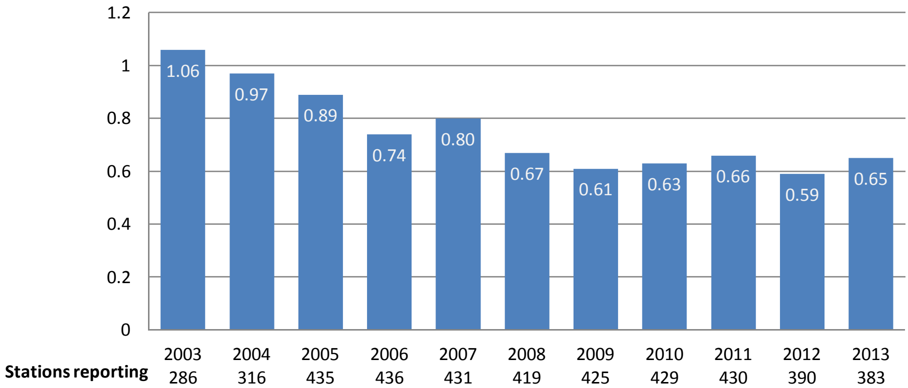

FIG. A.16. Mean rate of scrams: The number of automatic and manual scrams that occur per 7000 hours of operation.

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B. ADVANCED FISSION AND FUSION

B.1. Advanced fission

B.1.1. Water cooled reactors

In Canada, the Canadian Nuclear Safety Commission completed its third and final pre-licensing review of the 740 MW(e) Enhanced CANDU 6 (EC6) design, which incorporates a number of safety enhancements to meet the latest Canadian and international standards. Candu Energy also completed the development of the advanced CANDU reactor (ACR-1000), which incorporates very high component standardization and slightly enriched uranium to compensate for the use of light water as the primary coolant. The ACR-1000 has completed two phases of pre-licensing review. Candu Energy is also working with international partners to develop variants of the EC6 design to utilize advanced fuels including reprocessed uranium, MOX and thorium fuel.

In China, 29 PWRs are under construction. These include 650 MW(e) and 1080 MW(e) evolutionary PWRs based on existing operating plant technology, as well as newer AP1000 and European pressurized water reactor (EPR) designs. A new reactor, Hongyanhe-1, a CPR 1000 design reactor, was connected to the grid in February 2013. China continues to develop the CAP-1400 and CAP-1700 designs, which are large scale versions of the AP1000. At the same time, China continues to invest in research for the design of a Chinese supercritical water cooled reactor (SCWR).

In France, AREVA continues to market the 1600+ MW(e) EPR. It is also developing the 1100+ MW(e) ATMEA1 PWR, together with Mitsubishi Heavy Industries of Japan, and the 1250+ MW(e) KERENA boiling water reactor (BWR), in partnership with Germany’s E.ON. The first deployment of ATMEA1 is planned for the Sinop site in Turkey.

In India, five reactors are under construction, including four evolutionary 700 MW(e) PHWRs and one 1000 MW(e) water cooled water moderated power reactor (WWER). Kudankulam-1 (WWER) was connected to the grid in October 2013 and the second unit is undergoing startup testing. The Bhabha Atomic Research Centre (BARC) is finalizing the design of a 300 MW(e) advanced heavy water reactor (AHWR), which will use LEU and thorium MOX fuel with heavy water moderation and incorporate vertical pressure tubes and passive engineered safety features.

In Japan, two advanced boiling water reactors (ABWRs) are under construction. Hitachi-GE Nuclear Energy developed the 600 MW(e) class and 900 MW(e) class versions of the ABWR (ABWR-600 and ABWR-900) to respond to diverse needs. Toshiba Corporation modified the ABWR to satisfy US and EU requirements, and developed the US-ABWR and EU-ABWR, respectively. Japan continues to carry out research and development of innovative SCWR designs.

In the Republic of Korea, the construction of the first advanced power reactor, APR-1400, is progressing according to plan. The design certification process with the NRC for the APR-1400 is in progress with the application submitted in October 2013. In parallel, development of the 1500 MW(e) APR+ and APR-1000 continued in 2013.

In the United States of America, five PWRs, including four AP1000 reactors, are under construction. The NRC continues to review design certification applications for the economic simplified BWR (GE-Hitachi Nuclear Energy), US-EPR (AREVA NP) and US-APWR (Mitsubishi Heavy Industries).

Construction of seven WWER reactors continued in the Russian Federation, including two WWER-1000s and five WWER-1200s (NPP-2006). Plans to develop the WWER-1200A, as well as the WBER-600, WWER-600 (NPP-2006/2) and the WWER-1800 based on the current WWER-1200 design, continued. Furthermore, the Russian Federation pursued work on an innovative SCWR design, the WWER-SC, and construction is continuing on the KLT-40S, a small floating reactor for specialized applications.

B.1.2. Fast neutron systems

The important role of fast reactors and related fuel cycles for the long term sustainability of nuclear power has long been recognized. The achievable positive breeding ratio and the multi-recycling of the fissile materials obtained from the spent fuel from fast reactors allow full utilization of the energy potential of uranium and thorium. This technology guarantees energy supply for thousands of years and greatly enhances the sustainability of nuclear power by reducing high level and long lived radioactive waste.

However, successful large scale deployment of fast reactors can be achieved only if research and technology development can create the conditions to ensure that the full potential of the fast neutron systems and related closed fuel cycles is realized, and if the criteria of economic competitiveness, stringent safety requirements, sustainable development, and public acceptability are adequately satisfied.

Since 1960, significant fast reactor development and deployment programmes have been implemented worldwide, bringing the knowledge about fast reactor and associated fuel cycle technologies to a high level of maturity. The most mature fast reactor technology is the sodium cooled fast reactor (SFR). It has a history of 350 reactor years of experience acquired through the design, construction and operation of experimental, prototype, demonstration and commercial size SFRs operating in a number of States, such as China, France, Germany, India, Japan, the Russian Federation, the United Kingdom and the United States of America. Overall, SFR performance has been notable, with important achievements such as the demonstration of the feasibility of breeding new fuel through the fast reactor fuel cycle, with thermal efficiencies reaching values of 43–45%, which is the highest in the nuclear field. Indispensable experience in the decommissioning of several of these reactors has also been accumulated.

At present, four SFRs are in operation:

(a) China Experimental Fast Reactor (China);
(b) Fast Breeder Test Reactor (India);
(c) BOR-60 and BN-600 reactors (Russian Federation).

Two SFRs, Joyo and Monju in Japan, are in temporary shutdown. Construction of two SFRs is expected to be completed in 2014: the 500 MW(e) Prototype Fast Breeder Reactor in India (see Fig. B.1) and the commercial 880 MW(e) BN-800 reactor in the Russian Federation.

FIG. B.1. Prototype Fast Breeder Reactor under advanced construction at Kalpakkam, India. (courtesy of the Indira Gandhi Centre for Atomic Research).

In the Russian Federation, some experience with heavy liquid metals such as lead or lead–bismuth eutectic has been gathered from the operation of seven Project 705/705K nuclear submarines, equipped with a lead–bismuth cooled 155 MW(th) reactor.

Four different types of fast reactors (see Table B.1) are being developed at the national and international level in order to comply with higher standards of safety, sustainability, economics, physical protection and proliferation resistance. These are the SFR, the lead cooled fast reactor (LFR), the gas cooled fast reactor (GFR) and the molten salt fast reactor (MSFR).

B.1.3. Gas cooled reactors

The United Kingdom has been running commercial GCRs for many years. One Magnox reactor and 14 advanced GCRs are still in operation in United Kingdom and continue to play an important role in the area of high temperature gas cooled reactors (HTGRs) and to provide support to the operators along with numerous technical universities in addressing HTGR challenges. HTGRs are basically distinguished from the CO_2 GCRs in the United Kingdom by the use of coated particle fuel, higher gas outlet temperatures ($\geq 750^{\circ}C$) and the use of helium as a coolant. In contrast to the decline in the United Kingdom, HTGR development is being pursued in many Member States.

In China, the first concrete of the High Temperature Reactor–Pebble Bed Module (HTR-PM) was poured in December 2012 (see Fig. B.2), after meeting the requirements of the safety reassessment in the light of the Fukushima Daiichi accident. This 200 MW(e) industrial demonstration power plant consists of two 250 MW(th) reactor units, which are expected to be in operation by the end of 2017.

The Chinese fuel manufacturing technology has been established and fuel spheres are being tested internationally for normal and accident conditions. The construction of the new fuel fabrication plant in Baotou began in 2013 and full scale tests of the main components will be conducted in the completed 10 MW helium test loop. The HTR-10 research reactor underwent upgrades in 2013 and will be used for further operational experience, data gathering and testing.

The National Nuclear Energy Agency (BATAN, Badan Tenaga Nuklir Nasional) in Indonesia is studying a conceptual design for an HTGR, suitable for deployment outside the islands of Java, Madura and Bali. Activities are focused on a study of demand, economics, process heat and fuel fabrication.

TABLE B.1. FAST REACTOR DESIGNS

Design	Type	Power capacity	Designers
CFR-600	SFR, pool type reactor	600 MW(e)	China Institute of Atomic Energy (China)
Astrid	SFR, pool type prototype reactor	600 MW(e)	French Alternative Energies and Atomic Energy Commission, Électricité de France, AREVA NP, Alstom, Bouygues, Comex Nucléaire, Toshiba, Jacobs, Rolls-Royce and Astrium Europe (France)
FBR-1 and 2	SFR, pool type reactor	500 MW(e)	Indira Gandhi Centre for Atomic Research (India)
4S	SFR, small reactor	10 MW(e)	Toshiba (Japan)
JSFR	SFR, loop type reactor	750 MW(e) (medium scale) 1500 MW(e) (large scale)	Japan Atomic Energy Agency (Japan)
PGSFR	SFR, pool type prototype reactor	150 MW(e)	Korea Atomic Energy Research Institute (Republic of Korea)
BN-1200	SFR, pool type reactor	1220 MW(e)	Experimental Design Bureau for Machine Building (Russian Federation)
MBIR	SFR, pool type research reactor	100 MW(e)	Research and Development Institute of Power Engineering (Russian Federation)

TABLE B.1. FAST REACTOR DESIGNS (cont.)

Design	Type	Power capacity	Designers
PRISM	SFR, pool type reactor	311 MW(e)	GE-Hitachi (USA)
TWR-P	SFR, travelling wave reactor	600 MW(e)	TerraPower (USA)
MYRRHA	LFR, pool type lead–bismuth research reactor		Belgian Nuclear Research Centre (Belgium)
CLEAR-I	LFR, pool type lead–bismuth research reactor		Institute of Nuclear Energy Safety Technology (China)
ALFRED	LFR, pool type lead demo plant	125 MW(e)	Ansaldo Nucleare (Europe/Italy)
ELFR	LFR, pool type lead reactor	630 MW (e	Ansaldo Nucleare (Europe/Italy)
PEACER	LFR, pool type lead–bismuth demo plant	300 MW(e)	Seoul National University (Republic of Korea)
BREST-OD-300	LFR, pool type lead reactor	300 MW(e)	Research and Development Institute of Power Engineering (Russian Federation)
SVBR-100	LFR, small modular lead–bismuth reactor	101 MW(e)	AKME Engineering (Russian Federation)
ELECTRA	LFR, training lead reactor		Royal Institute of Technology (Sweden)
G4M	LFR, small modular lead–bismuth reactor	25 MW(e)	Gen4 Energy Inc. (USA)
ALLEGRO	GFR, experimental reactor		European Atomic Energy Community (Europe)

TABLE B.1. FAST REACTOR DESIGNS (cont.)

Design	Type	Power capacity	Designers
EM2	GFR, high temperature reactor	240 MW(e	General Atomics (USA)
MSFR	MSFR	1500 MW(e)	National Center for Scientific Research (France)

Note: GFR — gas cooled fast reactor; LFR — lead cooled fast reactor; MSFR — molten salt fast reactor; SFR — sodium cooled fast reactor.

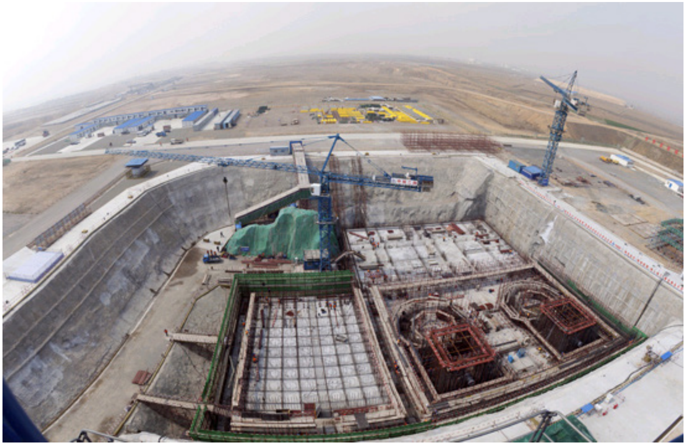

FIG. B.2. Construction site of the HTR-PM at Shidao Bay, Weihai City, China (courtesy of the Institute of Nuclear and New Energy Technology).

In Japan, the 30 MW(th) High Temperature Engineering Test Reactor (HTTR) is undergoing regulatory review. Further safety demonstration test is planned involving the loss of primary forced cooling plus loss of vessel cooling, simulating a station blackout. In response to the Fukushima Daiichi accident, the Japan Atomic Energy Agency has started designing a naturally safe HTGR based fully on inherent safety features and a clean burn HTGR for burning surplus plutonium in Japan. Hydrogen production development work is continuing.

The Republic of Korea continues to invest in test facilities for an HTGR for the production of hydrogen. Process heat applications are also planned in cooperation with industrial heat users. The development of coated particle fuel is progressing well and test irradiations will be conducted in the High Flux Advanced Neutron Application Reactor.

Work continued on the joint Russian–US gas turbine modular helium reactor (GT-MHR) project to dispose of weapons-grade plutonium by using it for electricity production and process heat applications. The focus is on key technologies for the reactor, such as fuel, graphite, high temperature materials, a power conversion system with a gas turbine and other reactor systems.

In Ukraine, a government decision allowed the possible deployment of HTGRs, reviving related research on industrial equipment and technologies.

In the United States of America, the Next Generation Nuclear Plant project focuses on tristructural isotropic fuel qualification, graphite and high temperature materials qualification, on test facilities to illustrate passive safety characteristics and on development of the licensing framework. The latest manufactured fuel has demonstrated excellent performance during irradiation at high operating temperatures (1250°C) and to very high burnup (19% fissions per initial metal atom), and at accident temperatures up to 1800°C, demonstrating improved safety and large margins in the reactor designs and fuel performance. The NRC has focused on resolving questions in the areas of licensing, specifically in basis event selection, source term determination, containment functional performance, and emergency planning.

The IAEA has been conducting two coordinated research projects on HTGRs on improving the understanding of irradiation creep behaviour of nuclear graphite, and on uncertainty analysis in HTGR reactor physics, thermalhydraulics and depletion.

The European Commission's Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D project aims to expand the European HTGR technology to support nuclear cogeneration with a focus on the safety aspects of the primary system coupled to an industrial application. In Poland, a government sponsored project was approved to investigate the possibilities of building an HTGR system. Activities in Germany are limited to selected safety research and participation in the EC HTGR programmes. In the Netherlands, the Nuclear Research and Consultancy Group at Petten and the Delft University of Technology support the EC programmes.

At the OECD/NEA, a code-to-code coupled neutronics/thermal fluids transient benchmark is being performed on the prismatic core design for HTGRs to study operational and accident conditions that include loss of coolant scenarios and moisture ingress.

B.1.4. Small and medium sized reactors

SMRs are potentially a source of power generation for Member States that have relatively isolated communities or otherwise limited electric grids. SMRs could also be an effective way of replacing obsolete, ageing or high carbon emitting power sources without any significant modification to the existing infrastructure. Member States have noted that seawater desalination using nuclear energy has been successfully demonstrated through various projects in some Member States and is generally cost effective, while recognizing that the economics of implementation will depend on site specific factors. SMRs are also considered as a potential technology option for cogeneration.

According to the classification adopted by the IAEA, small reactors are reactors with an electric power output of less than 300 MW(e) and medium sized reactors are reactors with an electric power output of 300–700 MW(e). At present, four advanced SMRs are under construction in four States: Argentina, China, India and the Russian Federation. SMRs are under development for all principal reactor lines including LWRs, heavy water reactors (HWRs), HTGRs and liquid metal fast reactors (LMFRs). The trend of development has been towards advanced small nuclear reactors to be deployed as a multiple modules power plant. Some water cooled SMRs adopt the integral approach for their primary system, in which components of the nuclear steam supply system are installed in a common vessel along with the reactor core. The progress in the development and deployment of small HTGRs and heavy liquid metal cooled fast reactors are reported in the relevant parts of this publication. Several States are advancing in the development and application of transportable nuclear power plants, including floating and marine based SMRs.

Approximately 45 innovative SMR concepts are at various stages of research and development. Some of the water cooled SMR designs being prepared for near term deployment are described in the following paragraphs.

In Argentina, deployment of the CAREM reactor — a small, integral type, pressurized LWR design with all primary components located inside the reactor vessel and an electrical output of 150–300 MW(e) — has started. The site excavation for the 27 MW(e) CAREM-25 prototype plant is already completed. The government issued the licence for construction for the CAREM-25 in October 2013. First concrete pouring is scheduled to take place in the first quarter of 2014.

China has developed 300 MW(e) and 600 MW(e) PWRs. Several units have already been deployed, and three CNP-600 units are under construction. Pakistan has also deployed two CNP-300 units imported from China and two additional CNP-300 units are under construction. Additionally, the CNNC has been developing the ACP-100 generating 100 MW(e), an integral PWR type SMR with horizontally mounted pumps into the reactor vessel. China plans to construct two ACP-100 units in Fujian province for electricity production and seawater desalination. The Shanghai Nuclear Engineering Research and Design Institute has been developing CAP-150, a 150 MW(e) small advanced reactor adopting passive safety features, and a floating 200 MW(th) SMR, the CAP-FNPP.

In France, DCNS is developing Flexblue, a small and transportable modular design reactor of 160 MW(e). Operated on the seabed, this water cooled reactor uses naval, offshore and passive nuclear technologies to take advantage of the sea, as an infinite and permanently available heat sink.

In India, many HWRs of 220 MW(e), 540 MW(e) and 700 MW(e) are in operation or under construction. The 304 MW(e) AHWR being developed by the BARC is at the detailed design phase.

In Italy, the Polytechnic University of Milan is continuing the design development of the International Reactor Innovative and Secure (IRIS), previously developed under an international consortium led by the Westinghouse Corporation. IRIS is an LWR with a modular, integral primary system configuration producing medium electrical power of 335 MW(e). The reactor concept is designed to satisfy the requirements of enhanced safety, improved economics, proliferation resistance and waste minimization.

In Japan, a medium sized 350 MW(e) LWR with an integral primary system called the integrated modular water reactor (IMR) has been developed. Validation testing, research and development for components and design methods and basic design development are under way to support licensing. The IMR is designed for both electricity production and cogeneration.

The Republic of Korea has developed the system integrated modular advanced reactor (SMART) design, with a thermal capacity of 330 MW(th). SMART is intended for combined use of electricity generation and seawater desalination. A pilot plant design project was launched for comprehensive performance verification. The 100 MW(e) SMART has obtained standard design approval from the Nuclear Safety and Security Commission in July 2012 and is now being prepared for first of a kind plant construction.

The Russian Federation is finalizing the construction of a barge mounted nuclear power plant with two 35 MW(e) KLT-40S reactors to be used for cogeneration of electricity and process heat. The KLT-40S is based on the commercial KLT-40 marine propulsion plant and is an advanced variant of the reactor that powers nuclear icebreakers. The 8.6 MW(e) ABV-6M is at the detailed design stage. It is an integral pressurized LWR with natural circulation of the primary coolant. The 50 MW(e) RITM-200, currently at the detailed design phase, is an integral reactor with forced circulation for nuclear icebreakers.

In the United States of America, four integral PWRs are under development. The B&W mPower reactor is a twin pack plant design of 180 MW(e) per module. NuScale Power envisages a nuclear power plant made up of twelve 45 MW(e) modules. The Westinghouse SMR is a 225 MW(e) conceptual design incorporating passive safety systems and proven components of the AP1000. The Holtec SMR-160 is a 160 MW(e) reactor that relies on natural convection, thereby eliminating the need for coolant pumps and dependence on external power sources. It is expected that applications for design certification review for the four concepts will be made to the NRC in the course of 2014–2016.

In 2012, the IAEA published the booklet Status of Small and Medium Sized Reactor Designs: A Supplement to the IAEA Advanced Reactors Information System (ARIS) [1]. Table B.2 lists water cooled SMR designs available for near and mid-term deployment.

TABLE B.2. WATER COOLED SMALL AND MEDIUM SIZED REACTOR DESIGNS AVAILABLE FOR NEAR AND MID-TERM DEPLOYMENT

Design	Type	Power capacity (MW(e))	Designer	Status
CAREM-25	Integral PWR, natural circulation	27	CNEA (Argentina)	One unit prototype under construction
CNP-300	2 loop PWR	315	CNNC (China)	Three units in operation Two under construction
ACP-100	Integral PWR	100	CNNC (China)	Detailed design
CAP-150	Integral PWR	150	SNERDI (China)	Conceptual design
Flexblue	Seabed moored small modular reactor	160	DCNS (France)	Conceptual design
AHWR300-LEU	Pressure tube	304	BARC (India)	Detailed design
IMR	Integral modular PWR, natural circulation	335	Mitsubishi Heavy Industries Ltd. (Japan)	Conceptual design
SMART	Integral PWR	100	KAERI (Republic of Korea)	Standard Design Approval granted July 2012
ABV-6M	Integral PWR, natural circulation	8.6	OKBM (Russian Federation)	Detailed design
VBER-300	Integral PWR	325	OKBM (Russian Federation)	Detailed design

TABLE B.2. WATER COOLED SMALL AND MEDIUM SIZED REACTOR DESIGNS AVAILABLE FOR NEAR AND MID-TERM DEPLOYMENT (cont.)

Design	Type	Power capacity (MW(e))	Designer	Status
RITM-200	Integral PWR	50	OKBM (Russian Federation)	Detailed design
KLT-40S	Barge mounted floating nuclear power plant	70	OKBM (Russian Federation)	Two units in final stage of construction
WWER-300	Integral PWR	300	Gidropress (Russian Federation)	Detailed design
VK-300	BWR	250	RDIPE (Russian Federation)	Conceptual design
UNITHERM	Very small, integral PWR, with natural circulation	2.5	RDIPE (Russian Federation)	Conceptual design
Shelf	Seabed moored, small modular reactor	6	RDIPE (Russian Federation)	Conceptual design
IRIS	Integral PWR	335	IRIS International Consortium (Italy)	Conceptual design
B&W mPower	Integral PWR (twin pack of 180 MW(e))	360	B&W Generation Power (USA)	Detailed design
NuScale	Integral natural circulation PWR (12 modules of 45 MW(e))	45	NuScale Power (USA)	Detailed design

TABLE B.2. WATER COOLED SMALL AND MEDIUM SIZED REACTOR DESIGNS AVAILABLE FOR NEAR AND MID-TERM DEPLOYMENT (cont.)

Design	Type	Power capacity (MW(e))	Designer	Status
Westinghouse SMR	Integral PWR	225	Westinghouse Electric Corporation, USA	Detailed design
Holtec SMR-160	Integral PWR	160	Holtec Corporation, USA	Detailed design

Note: BARC — Bhabha Atomic Research Centre; BWR — boiling water reactor; CNEA — National Atomic Energy Commission (Comisión Nacional de Energía Atómica); CNNC — China National Nuclear Corporation; KAERI — Korea Atomic Energy Research Institute; OKBM — Experimental Design Bureau for Machine Building; PWR — pressurized water reactor; RDIPE — Research and Development Institute of Power Engineering; SNERDI — Shanghai Nuclear Engineering Research and Design Institute.

B.1.5. International initiatives on innovative nuclear systems

Owing to increasing concerns over energy resource availability, climate change and energy security, and since nuclear energy has the potential to make a significant contribution to meeting the world's growing energy demand, a number of international initiatives on innovative nuclear systems have been launched in the last decades.

In particular, at the turn of the century, a number of IAEA Member States recognized the need to take action to ensure that nuclear energy was developed in a sustainable manner. As a result, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated in 2000 as an IAEA project, following a General Conference resolution, to help ensure that nuclear energy is available to contribute to meeting the global energy needs of the twenty-first century, sustainably. The major objective was to bring together technology holders and users to jointly consider international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles. The INPRO Group is funded mainly from the European Commission and the 38 Member States that are members of INPRO. Kenya joined INPRO in 2013 as the 39th member.

INPRO is revising its methodology which takes a holistic approach to assess innovative nuclear systems in seven areas: economics, infrastructure, waste management, proliferation resistance, physical protection, environment and safety. Belarus completed a Nuclear Energy System Assessment (NESA) based on this methodology and the report was published by the IAEA as a reference document for Member States [2]. NESAs in Indonesia, Romania and Ukraine are under way.

The Generation IV International Forum (GIF) is a cooperative international endeavour organized to carry out the research and development needed to establish the feasibility and performance capabilities of the next generation of nuclear energy systems. With its 13 members, the GIF focuses on six nuclear energy systems as described in A Technology Roadmap for Generation IV Nuclear Energy Systems [3], issued in 2002:

- Gas cooled fast reactors (GFRs);
- Very high temperature reactors (VHTRs);
- Supercritical water cooled reactors (SCWRs);
- Sodium cooled fast reactors (SFRs);
- Lead cooled fast reactors (LFRs);
- Molten salt reactors (MSRs).

GIF members interested in implementing cooperative R&D on one or more of the selected systems have signed corresponding System Arrangements. Within each System Arrangement, a limited number of common R&D projects have been established, with well defined deliverables, milestones and time schedules, and within a clearly defined contractual framework.

The GIF and INPRO hold annual interface meetings focusing on specific assessment methodologies in the area of economics, proliferation resistance and physical protection, risk and safety, as well as advanced simulation.

Another important activity launched in 2011 by the GIF, in cooperation with the IAEA, in the area of SFR, is the development of Safety Design Criteria (SDC) aimed at harmonizing safety requirements among the design organizations represented within the GIF, as well as quantifing the high level of safety expected for SFR Gen-IV systems. A Phase 1 SDC report was issued by the GIF in 2013 and is currently being reviewed by the IAEA, the OECD/NEA, the Multinational Design Evaluation Programme (MDEP) and some regulators from GIF Member States. Phase 2 of the SDC report will quantify the design criteria and will include the development of detailed guidelines on how to implement the general criteria.

The GIF's scope of work covers the feasibility and performance phases of R&D, and not its demonstration phase. Therefore, prototypes are not one of the Forum's prerogatives.

The Sustainable Nuclear Energy Technology Platform (SNETP) was officially launched in the European Union in 2007 to promote research, development and demonstration for the nuclear fission technologies necessary to achieve the European Strategic Energy Technology Plan (SET-Plan).

Today, the SNETP gathers more than 100 European stakeholders from industry, research, academia, technical safety organizations, non-governmental organizations and national representatives. Activities focus on maintaining safety and competitiveness in fission technology, on providing long term waste management solutions for the year 2020, on completing the demonstration of a new generation of fission reactors with increased sustainability, and on enlarging nuclear fission applications beyond electricity production by 2050.

The European Sustainable Nuclear Industrial Initiative (ESNII), launched by the European Union in 2010, addresses the European need for the demonstration of Gen-IV fast neutron reactor technologies, together with the supporting research infrastructures, fuel facilities and R&D work. Its work is focused on developing two parallel technologies: the sodium cooled fast neutron reactor technology as the reference solution, with the construction of a prototype around 2020 in France that will strongly support this technology; and an alternative technology — either the LFR or GFR — with the construction of an experimental reactor to demonstrate the technology, in another European State willing to host this programme.

B.1.6. Cogeneration for non-electric applications of nuclear energy

Coupling nuclear reactors to industrial applications (i.e. nuclear cogeneration) has several practical advantages such as:

- — Savings achieved by reusing waste heat from the nuclear power plants;
- — Increased overall plant thermal efficiency;
- — Enhanced electric grid flexibility;
- — Reduced GHG emissions and environmental impact.

In general, all nuclear reactors can be used for non-electric applications. Depending on the technology, reactor type, fuel type and temperature level, the cogeneration process may be different. Some of the heat usually discharged to the environment can be used for desalination and district heating as a bottoming cycle. Accordingly, total heat utilization efficiency can be increased up to 70–80%, compared with about 33% for existing LWRs. LMFRs, LWRs and SCWRs are all suitable candidates for cogeneration with low temperature process heat applications such as district heating and desalination systems. High temperature reactors (e.g. HTGRs, GFRs and MSRs) are more suitable for cogeneration with high temperature process heat applications and hydrogen production. The indirect cycle approach is considered suitable for all reactors (see Fig. B.3).

Cogeneration represents an ideal option for many energy intensive applications such as fuel synthesis (including hydrogen production), coal gasification and oil extraction. Nuclear energy may represent a significant option to meet market potential for cogeneration options. In the low temperature range, district heating (80–150°C) and seawater desalination (65–120°C) are the most obvious applications. In the medium temperature range, a large number of heat applications such as petroleum refining, oil shale and oil sand processing exist. High temperature heat is typically demanded in petrochemical, steel and hydrogen production.

The technical and commercial viability of LWRs has been demonstrated at numerous operating plants in various States for over 30 years. Bulgaria, Hungary, the Russian Federation, Slovakia, Switzerland and Ukraine, where district heating is common practice with fossil fired plants, also have district heating systems coupled with nuclear power plants. The heating capacity provided by these nuclear plants fall in the range of 20–250 MW(th), typically a minor fraction of the total reactor thermal power. District heating water or steam is heated to 130–150°C using steam extracted from the turbine.

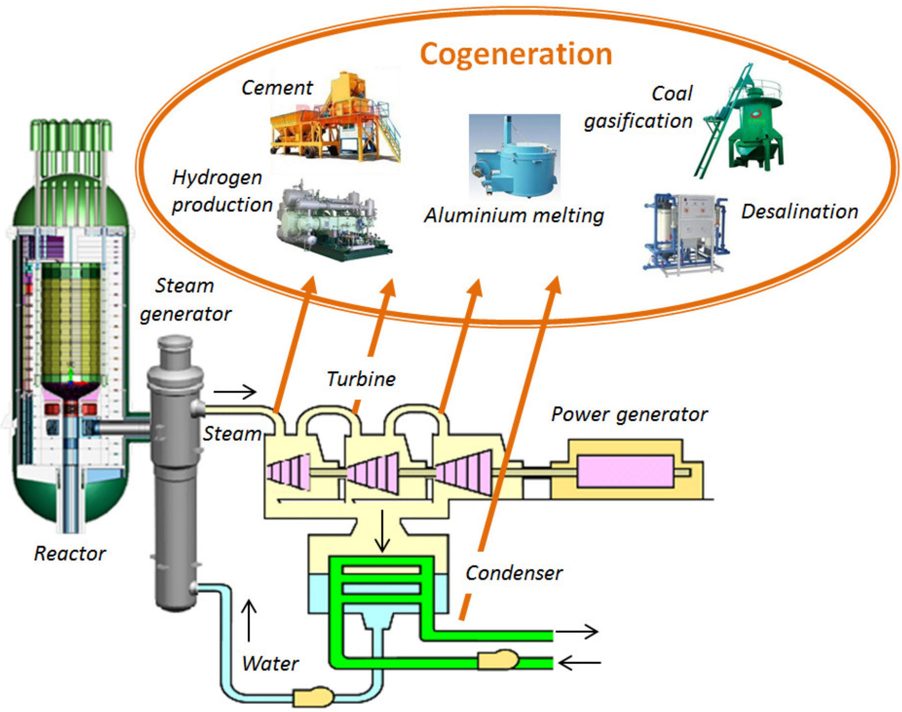

FIG. B.3. Schematic representation of cogeneration.

Desalination has been cogenerated with LWR plants in Japan and the United States of America, and with the SFR BN-350 in Kazakhstan. In Japan, all of the nuclear power plants are located at sea sites. Several nuclear power plants operated by Kansai Electric Power, Kyushu Electric Power and Shikoku Electric Power companies have seawater desalination systems using heat or electricity from the nuclear plant to produce feedwater make-up systems for the steam generators and for on-site supply of potable water. Multi-effect distillation (MED), multi-stage flash (MSF) and reverse osmosis (RO) desalination processes have been used. The individual desalination capacities are in the range of 1000–3000 m^3/day.

Cogeneration for industrial applications was demonstrated by Germany's Stade nuclear power plant, a 1892 MW(th), 640 MW(e) PWR, which supplied steam for a salt refinery located 1.5 km away. The steam supply by the nuclear power plant had very high time availability with good operating experience between 1983 and 2003. Another example is the 970 MW(e) PWR of the Gösgen nuclear power plant, in Switzerland, which has been feeding process steam to a nearby cardboard factory since 1979. The process steam is generated in a tertiary steam cycle by live steam extracted from the PWR. It is then piped over a distance of 1.75 km to the factory. Switzerland's Beznau nuclear power plant, with its two 365 MW(e) PWR units, is also used for district heating.

Cogeneration has also been demonstrated using CANDU reactors. For instance, Canada's Bruce nuclear power plant successfully provided heat for heavy water production while generating electricity for two decades. In 2008, a desalination plant with a capacity of 6300 m^3/day was coupled to the Madras Atomic Power Station, in Kalpakkam, India. The hybrid desalination process combines MSF and RO. The final water mixture is supplied for industrial/municipal uses. Utilizing 1 MW(e) of thermalelectric energy can produce 1500 m^3/day water with MSF and 1800 m^3/day using RO. Therefore, following the retrofit the production of 6300 m^3/day would be achieved with a reduction of approximately 4 MW electric output from the nuclear power generation. In 2010, the world's newest nuclear cogenerating plant was commissioned by Pakistan. This is another retrofitting project, this time to couple an MED unit to the existing Karachi nuclear power plant, a 125 MW(e) CANDU-HWR plant. The completed desalination plant produces 1600 m^3/day from seawater. The same site had been running a 454 m^3/day RO plant for in-house water use.

All high temperature reactors are suitable for cogeneration. As seen in Table B.3, GCR concepts such as the pebble bed reactor (PBR), prismatic modular reactor (PMR) and GFR can provide heat for industrial processes and hydrogen production. In order to benefit from them, the European Union has launched the Nuclear Cogeneration Industrial Initiative (NC2I). In addition, the VHTR system is considered the prime candidate for large scale hydrogen production. Cogeneration of heat and power makes the VHTR an attractive heat source for large industrial complexes. The VHTR could be deployed in refineries and petrochemical industries in order to replace other sources in large amounts of process heat at different temperatures, including hydrogen generation for upgrading heavy and sour crude oil.

Cogeneration plants will result in additional advantages if constructed as co-located plants because they can then share many conventional utilities and infrastructures, which will consequently reduce both costs and land use. Typically, more attention is given to the safety aspects achieved by coupling the nuclear power plant with the cogeneration unit where an intermediate loop is considered.

TABLE B.3. POTENTIAL FOR ENERGY PRODUCT APPLICATIONS OF THE MOST PROMISING GEN-IV GAS COOLED REACTOR SYSTEMS

Reactor	PBR	PMR	GFR	VHTR
Thermal power (MW(th))	250	600	600	600
Electric power (MW(e))	110	286	288	300–360
Outlet temperature (°C)	850	850	850	950–1300
Primary pressure (MPa)	7.75	7.07	7.0	6.8–8.0
Hydrogen production	Yes	Yes	Yes	Yes
Desalination of water	Yes	Yes	Yes	Yes
High temperature process heat (petroleum refineries and desulphurization of heavy oil)	Yes	Yes	Yes	Yes
District heating	Yes	Yes	Yes	Yes

Note: GFR — gas cooled fast reactor; PBR — pebble bed reactor; PMR — prismatic modular reactor; VHTR — very high temperature reactor.

B.2. Nuclear fusion

Developing nuclear fusion science, engineering and technology to a point where fusion energy can be supplied to the grid is one of the most exciting challenges of the twenty-first century, and potentially one of the most rewarding.

With the establishment of the International Thermonuclear Experimental Reactor (ITER) project in 2006, several States of the world have joined efforts to demonstrate the scientific and technological feasibility and safety features of fusion energy in excess of 500 MW for peaceful purposes.

On 10 November 2012, the French Government published Decree 2012-1248 authorizing the creation of the ITER nuclear facility, representing a landmark achievement for ITER and the worldwide fusion development programme. Construction on the ITER site is in progress with the new headquarters building in use since October 2012. The 104 km ‘special itinerary’ to allow the transport of large components from the port in Marseille to the ITER site is also complete and was successfully tested in September 2013 using a test convoy: an 800 t trailer replicating the dimensions of ITER’s largest and heaviest component loads (see Fig. B.4). This successful precursor paves the way for the deliveries of actual ITER components, which will begin in the middle of 2014.

FIG. B.4. The ITER site as of September 2013 (left). The 800 t trailer with remote controlled vehicle, replicating the weight and dimensions of the largest ITER loads (10 m tall, 33 m long and 9 m wide), travelled at an average speed of 5 km/h for four consecutive nights to test the 104 km long 'special itinerary' (right) (courtesy of ITER).

As of 21 November 2013, seven years to the day after the signature of the ITER Agreement in Paris, all major contracts for on-site civil works, a crucial milestone for the project, were signed and the manufacturing of key components were progressing steadily within the respective industries. This includes critical components, such as superconducting coils, the vacuum vessel and the cryostat. Approximately 500 construction workers were active on the ITER site in 2013. This number will rise to 3000 at the peak of construction activity in 2014–2015. The current overall schedule includes machine completion and first plasma operation in November 2020. In November 2013, a significant decision, which will result in cost savings for the project, was taken that operations will commence with a full tungsten divertor (the plasma power exhaust area in a magnetic confinement fusion device), rather than a carbon fibre divertor, which would have been replaced during the second phase of operations with a tungsten divertor.

With ITER construction under way, the worldwide magnetic fusion programme is in a transition to one increasingly focused on the production of fusion energy on an industrial, power plant scale. Many States are independently developing programme plans and initiating new R&D activities leading to a demonstration of fusion energy's readiness for commercialization. Collectively these plans and activities comprise a 'demonstration fusion power plant' (DEMO) programme, even though there is no single or coordinated view of the roadmap to the demonstration of electricity generation from fusion.

Resolving DEMO scientific and technical issues and facility requirements is of common interest, even if States have different emphases and priorities. The IAEA established in 2012 a series of annual DEMO programme workshops to facilitate international cooperation on defining and coordinating activities. Immediately after the 24th IAEA Fusion Energy Conference held in San Diego, United States of America, the first IAEA DEMO programme workshop was held in October 2012 at the University of California, Los Angeles. Workshop discussions highlighted that the ITER roadmap must include both integrated fusion nuclear facilities and fusion material irradiation facilities. Planning for some of these major facilities is now under way. The roadmap, as well as the optimum modes of collaboration, will be defined by the initiatives that are taken by parties to construct and exploit these large scale facilities.

As an example, an official roadmap to the realization of fusion energy has recently been released under the European Fusion Development Agreement (EFDA) [4]. This roadmap breaks down the quest for fusion energy into eight missions. For each mission, it reviews the current status of research, identifies open issues, proposes a research and development programme and estimates the required resources. It points out the needs to intensify industrial involvement and to seek all opportunities for collaboration outside Europe. According to this roadmap, a DEMO fusion plant producing net electricity for the grid at the level of a few hundred megawatts is foreseen to start operation in the early 2040s and will be a step towards a commercial fusion power plant in Europe. The transition of the European fusion programme from a science driven to an industry driven and technology driven venture is supported by the replacement, as of January 2014, of the EFDA by the new EURO fusion consortium. This new organization will have a project oriented approach, supporting roadmap missions, research in basic plasma processes and the preparation of the new ITER generation of scientists. Similar roadmap initiatives are gradually emerging in other ITER party States.

The second IAEA DEMO programme workshop was held in December 2013 at the IAEA's Headquarters with discussions organized around three major topics: fusion physics engineering design codes; plasma power exhaust and impurity control; and plasma scenarios and control.

The National Ignition Facility (NIF), at the Lawrence Livermore National Laboratory, United States of America, uses an inertial confinement scheme involving high power lasers to generate fusion reactions with the prospect of achieving high energy gain from heating and compressing a cryogenic deuterium–tritium pellet. In 2013, the NIF met many of the requirements believed necessary to achieve ignition, which is the point where the reaction releases as much energy as went into the system as a whole: sufficient X ray intensity in the hohlraum, accurate energy delivery to the target and desired levels of compression.

However, at least one major hurdle, the premature breaking apart of the capsule enclosing the fuel mixture, remains to be overcome.

The 25th IAEA Fusion Energy Conference, the leading event in the field, will be held in October 2014 in St. Petersburg, Russian Federation.

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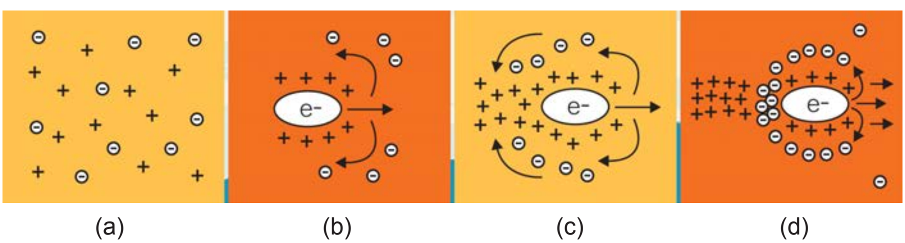
C. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

C.1. Accelerators

The field of accelerator development is rapidly evolving, allowing for innovative applications with societal impact. To date, development in accelerator technologies has faced two major parameters when defining the shape and length of an accelerating machine: the maximum magnetic field that can be applied to a beam of accelerated particles; and the maximum accelerating gradient the machine can achieve. Currently, the upper achievable magnetic field is about 20 T, assuming that superconductors are used. Some progress is expected with the advent of new high temperature superconductors that may allow for fields of up to 30 T. Such an increase in magnetic field strength is certainly a big step forward; however, it cannot be taken as a breakthrough in accelerator R&D. A breakthrough has, however, come through the huge accelerating gradients achieved recently: instead of the 20–50 MeV/m that a conventional accelerator can reach, a plasma wakefield accelerator (PWFA) can accelerate an electron beam (EB) up to 200 GeV within the same distance. In a PWFA, a high intensity, low energy EB (or an intense, short laser pulse) excites the plasma, which is formed by ionizing a gas with a laser or through field ionization by an incoming electron bunch itself. Figure C.1 illustrates the working principle.

The potential of the plasma based accelerators to provide powerful EBs within a very small fraction of the space required by conventional accelerators is vast. The possible reduction in length with the corresponding reduction in cost may allow for 'table top' laser plasma accelerators in the future. As demonstrated at the Lawrence Berkeley National Laboratory, United States of America, a laser



Note: (a) Positive ions and free electrons forming a plasma. (b) An electron bunch enters the plasma and repels all free electrons. Positive ions are attracted around the bunch. (c) The already displaced free electrons are now attracted by the positive ions left behind the bunch. (d) The free electrons in their new position behind the bunch accelerate the electron bunch.

FIG. C.1. Plasma acceleration (courtesy of symmetry).

pulse through a capillary with dimensions smaller than those of a palm filled with hydrogen plasma creates a wake field that can accelerate an EB to 1 billion eV in just 3.3 cm.

Synchrotron light is produced by electrons circulating in a ring at almost the speed of light. Electrons are deviated by the magnetic field of bending magnets distributed all along the circumference. The synchrotron light is composed of bright infrared, ultraviolet and X ray light. The beams of light are emitted tangentially to the trajectory of the electrons following a straight direction towards the beamlines (i.e. instruments composed of a series of cabins). The first cabin comprises instruments like slits, filters, mirrors and monochromators.

Synchrotron radiation allows for the study of the structural details of matter, notably on a scale comparable to the placement of individual atoms. The synchrotron light based analytical methods are capable of providing information on the spatial structure of the materials, on the chemical and electronic structure, on microstructure and on the properties of surfaces, interfaces, thin films and multilayers. Synchrotron radiation can be used to create cross-sectional images of matter to analyse its behaviour at nanosecond intervals. Therefore, it is an indispensable tool for applied research in a great variety of areas, such as the development of new materials with relevance to nanotechnology, electronics and communications, energy generation and storage, medicine and health care, transport and the environment.

Accelerators are also used to produce radioisotopes such as ^{11}C, ^{64}Cu and ^{18}F. An IAEA coordinated research project, launched in 2011, focuses on the direct production of the key medical isotope ^{99}Mo and its decay product, ^{99m}Tc, in cyclotrons. Unlike the typical fission process of producing ^{99}Mo in a reactor using uranium targets, these technologies use ^{100}Mo targets. A linear accelerator can be used to produce ^{99}Mo through the transmutation of enriched ^{100}Mo, while cyclotrons can be used to produce ^{99m}Tc directly by irradiating ^{100}Mo.

Canada's programme in this field is led by the University of Alberta (cyclotron), TRIUMF (cyclotron) and Prairie Isotope Production Enterprise (linear accelerator). Activities are under way to demonstrate commercial quantities of isotope production, with TRIUMF recently announcing production capacity enough to supply 10–20 hospital nuclear medicine departments. A significant environmental and economic advantage of these two technologies is that little waste is generated and projects have demonstrated efficiency in the 90% range with respect to ^{100}Mo recycling. Work is under way to meet regulatory requirements and to address remaining technical and commercial challenges.

Through dedicated programmes and activities, the IAEA's Nuclear Spectrometry and Applications Laboratory (NSAL) supports the development of laboratory and accelerator based X ray spectrometry techniques for interdisciplinary applications and fundamental research. Based on a research and development project launched in 2011 by NSAL, the IAEA and Elettra facility of Italy have signed a contract in 2013 to construct and operate a new X ray fluorescence beamline. The novel experimental station provided by the IAEA was installed at the beamline in the last quarter of 2013. This will enable hands-on training for Member States on advanced X ray spectrometry techniques such as X ray fluorescence (XRF), total reflection X ray fluorescence, and grazing incidence X ray fluorescence/grazing exit X ray fluorescence, in combination with X ray reflectivity and X ray absorption spectroscopy, and on fostering relevant research activities and academic programmes.

For this purpose, a coordinated research project was launched in 2013 to increase the quality and the competitiveness of Member States' research in synchrotron radiation based X ray spectrometry methods by supporting advanced hands-on training, by guiding experimental work and by conducting research activities at the ultra-high vacuum chamber (UHVC) end station (see Fig. C.2) of the Elettra XRF beamline.

When characterizing historical artefacts, radiation damage is a common concern of scientists, curators, conservators and archaeologists. Owing to the high dose deposited, there is a risk of degradation of the material under study. Damage can sometimes be visible to the human eye, such as the formation of colour centres in glass or the browning of organic compounds. Even without direct visual consequences in the sample or object, the potential loss of information, or worse the retrieval of misleading or biased information, from an area damaged by radiation is a major analytical risk.

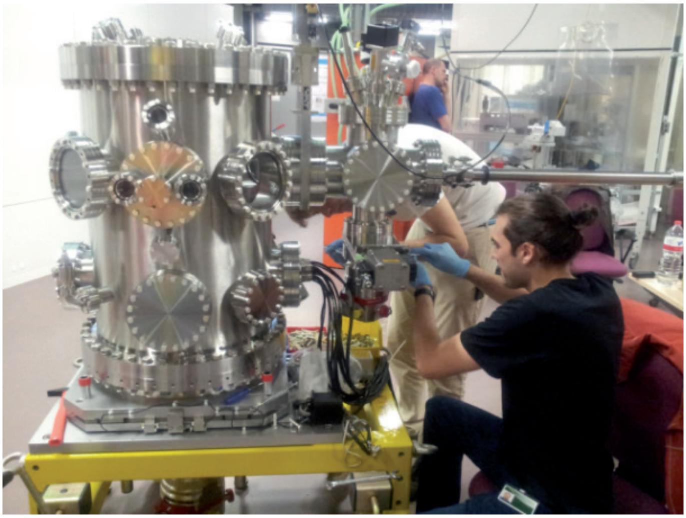
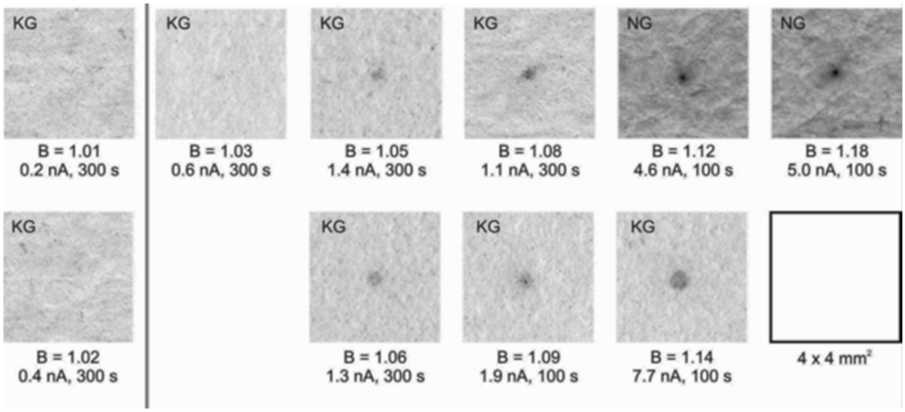


FIG. C.2. Assembly of the UHVC end station.



Note: NG is ungrounded rag paper. KG is rag paper ground with bone white. The black value B (essentially the ratio between the grey scale values of a spot and its environment) indicates the amount of beam induced discoloration. For the leftmost figures with B up to 1.02, separated from the rest by a vertical line, no effect is visible.

FIG. C.3. Enlarged images of irradiated paper areas after accelerated ageing, ordered by increasing exposure to protons (reproduced from Ref. [1] with permission from Elsevier).

To date, there have been a few systematic studies of the discolouration resulting from the ion beam analysis of paper: for example, a study reporting the marking of two types of artificially aged rag paper (with bone ground and with no ground) resulting from exposure to MeV protons under a variety of conditions [1]. Figure C.3, taken from this study, shows a typical set of observations. The authors conclude that, provided that the exposure conditions are kept below certain criteria, no visible marking is observed, even after a process of humidity and temperature cycling aimed to simulate ageing of around 100 years.

Radiation damage to cultural heritage materials is an important mechanism in ageing and degradation. However, a similar process occurs when cultural heritage samples are irradiated for their characterization and preservation. The IAEA is addressing these issues through Technical Meetings, round robin exercises and the development of best practices and protocols. The objective is to propose a new definition of how to characterize radiation induced effects in cultural heritage materials. Such a definition would:

— Be based beyond immediate visual inspection;
— Identify relevant activities in neighbouring fields to provide valuable information on damage mechanisms to the diverse and sometimes unique cultural heritage materials;

— Review radiation damage monitoring strategies;
— Propose mitigation strategies.

The IAEA is launching the new Accelerator Knowledge Portal for the benefit of accelerator users, researchers and analytical service providers worldwide. The knowledge portal offers not only a database of Megavolt particle accelerators in the world, but also has several networking and community features to bring together the ion beam accelerator community, as well as to provide information to accelerator users and policy makers.

C.2. Research reactors

Research reactors are primarily used to provide neutrons for research and various applications, including education and training (see Table C.1). Research reactor power ratings are designated in megawatts and their output can range from zero (e.g. critical or subcritical assemblies) up to 200 MW(th), as compared with 3000 MW(th), i.e. 1000 MW(e), for a typical large power reactor.

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

Type of application	Number of research reactors involved[a]	Member States hosting utilized facilities
Teaching/training	174	54
Neutron activation analysis	128	54
Radioisotope production	96	43
Material/fuel irradiation[b]	80	29
Neutron radiography	72	41
Neutron scattering	50	33
Transmutation (silicon doping)	30	19
Geochronology	26	22
Transmutation (gemstones)	21	12

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

Type of application	Number of research reactors involved[a]	Member States hosting utilized facilities
Boron neutron capture therapy, mainly R&D	18	12
Other[c]	137	35

Source: IAEA Research Reactor Database, available at http://nucleus.iaea.org/RRDB.

[a] Out of 280 research reactors considered (245 operational, 20 temporary shutdown, 5 under construction and 10 planned; 31 December 2013).

[b] The IAEA is developing a comprehensive catalogue Capabilities and Capacities of Research Reactors towards the Deployment of Innovative Nuclear Energy Systems and Technologies.

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

As of 31 December 2013, there were 245 operating research reactors in the world.[7] In addition, there were 20 research reactors in temporary shutdown mode, and 142 in long term shutdown. Of the operating reactors, 57 are high capacity, operating at power levels higher than 5 MW and offering higher neutron fluxes. An additional 338 research reactors have been decommissioned. The majority of the operating research reactors remain heavily underutilized, are very old and therefore require continuous ageing management, modernization and refurbishment.

In recent years, the interest of Member States in developing research reactor programmes has been steadily growing. A number of Member States are in different stages of new projects and some want to use their first research reactor as the State’s introduction to nuclear science and technology infrastructure. Construction of new research reactors is ongoing in France, Jordan (see Fig. C.4) and the Russian Federation. Several Member States have formal plans to build new research reactors: Argentina, Belgium, Brazil, India, the Republic of Korea, the Netherlands, the Russian Federation, Saudi Arabia and South Africa.

[7] Source: IAEA Research Reactor Database, available at http://nucleus.iaea.org/RRDB.

FIG. C.4. The Jordan Subcritical Assembly of zero power was given an operational licence in June 2013 (left, courtesy of Jordan University of Science and Technology). Construction of the 5 MW Jordan Research and Training Reactor was 49% complete as of October 2013 (right, courtesy of the Jordan Atomic Energy Commission).

Other Member States, such as Bangladesh, Belarus, Kuwait, Lebanon, Nigeria, Sudan, Thailand, Tunisia, the United Republic of Tanzania and Viet Nam, are considering building new research reactors.[8]

As older reactors are decommissioned and replaced by fewer multipurpose ones, the number of operational research reactors and critical facilities is expected to continue to decrease. Greater international cooperation will be required to ensure broad access to these facilities and their efficient use. In 2013, research reactor regional networks or coalitions, facilitated by the IAEA,[9] helped foster international cooperation and assisted research reactors in expanding their stakeholder base.

The Global Threat Reduction Initiative (GTRI), launched by the United States of America, continued throughout 2013 to carry out its mission to minimize the presence of HEU in the civilian nuclear sector worldwide. In 2009, the scope of GTRI was expanded from 129 to approximately 200 research reactors that operated with HEU fuel and, by the end of 2013, 88 of these had been converted to LEU fuel or shut down before conversion.

A recent good example of versatile international support and cooperation related to HEU minimization is the development of an HEU fuel removal and decommissioning plan for the FOTON research reactor in Tashkent, Uzbekistan. As of the end of 2013, the Uzbekistan Government was working to fund the implementation of the reactor site decommissioning.

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[8] The IAEA publication IAEA Nuclear Energy Series No. NP-T-5.1, Specific Considerations and Milestones for a Research Reactor Project [2], is aimed at helping Member States in this area.

[9] The IAEA has assembled several different research reactor coalitions in the Baltic, the Caribbean (which includes participation from Latin America), Central Africa, Central Asia, Eastern Europe and the Mediterranean.

FIG. C.5. Tightening the bolts on special transport packages carrying spent HEU fuel from Viet Nam's Dalat Nuclear Research Institute to the Russian Federation (left). Placing a protective overpack on a transport cask containing spent HEU fuel from the BRR in Hungary (right). This overpack was designed to permit air transport.

Furthermore, in the Czech Republic, the LVR15 research reactor was entirely converted to LEU fuel and the final 70 kg of spent HEU fuel were shipped back to the Russian Federation in April 2013. In Viet Nam, following the HEU to LEU fuel conversion of the TRIGA research reactor in Dalat, the final inventory of nearly 12 kg spent HEU fuel was returned to the Russian Federation in July 2013. In Hungary, core conversion of the 10 MW Budapest Research Reactor (BRR) was completed in January 2013, and its final batch of over 49 kg of HEU was flown to the Russian Federation during October and November 2013 (see Fig. C.5). The completion of these projects resulted in all three Member States becoming HEU fuel free.[10]

Conversion to LEU and repatriation of HEU fuel is often followed by significant infrastructure upgrades. For example, the IAEA's Peaceful Uses Initiative is funding a comprehensive modernization programme at Mexico's TRIGA Mark III research reactor. In Ukraine, an LEU fuelled, accelerator driven, subcritical facility is being constructed at the Kharkov Institute of Physics and Technology with financial and technical support from the United States Department of Energy, following the repatriation of all HEU to the Russian Federation.

China continued its efforts to convert its miniature neutron source reactors from HEU to LEU, and is planning on working with Member States that have purchased such reactors to help convert them and repatriate the HEU fuel.

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[10] Altogether, more than 2000 kg of Russian supplied HEU have been transferred to the Russian Federation in 56 shipment operations since a joint initiative of the IAEA, the Russian Federation and the United States of America began in 2002.

Following an abatement of the ^{99}Mo supply shortages during 2012, operational challenges at processing facilities and older research reactors returned in 2013. Owing to changes in demand management as well as some diversification in supply, the shortages did not result in a crisis on the scale witnessed between 2007 and 2010. The conversion of medical isotope production processes from HEU to LEU continued. Australia and South Africa continue to be the major suppliers of non-HEU ^{99}Mo, and South Africa continued the conversion of its processes to the exclusive use of LEU. Two other major medical isotope producers, Belgium and the Netherlands, continued their plans to convert their commercial scale production processes from HEU to LEU.

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 was made prior to 2013, 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 the timely commercial availability of qualified LEU fuels.

Following the conversion of relevant TRIGA reactors, global demand for TRIGA fuel has decreased. Since 2010, no new fuel elements have been provided, challenging the ongoing operation of several TRIGA reactors worldwide. Owing to these common threats, the TRIGA community initiated the Global TRIGA Research Reactor Network (GTRRN) in June 2012. The GTRRN was formalized in November 2013 in Vienna by establishing its Steering Committee. The GTRRN will address the challenges of the 38 operating TRIGA facilities worldwide, mainly finding alternatives to issues such as fresh fuel supply, the extension of the US repatriation programme for spent nuclear fuel, enhanced utilization, ageing management, operation and maintenance.

In 2013, activities continued to promote and enhance the utilization of research reactors for education and training purposes. International projects included those on finding ways to increase the number, types and quality of training courses, providing access for young professionals in developing countries around the world, and involving research reactors in basic and specific education related to nuclear science and technology.

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D. NUCLEAR TECHNIQUES TO INCREASE ANIMAL PRODUCTION WHILE REDUCING GREENHOUSE GASES

Producing sufficient food to satisfy the consumption demands of the growing human population has been a global challenge. The challenge is compounded by the environmental impact of food acquisition, which requires energy expenditure and thus contributes to GHG emissions. The agriculture sector, including livestock, accounts for about 22% of total global emissions [1]. Good livestock production practices can both increase the quantity and quality of animals and animal products, and reduce GHG emissions.

This section focuses on the innovative nuclear and nuclear related technologies that can be developed and applied to improve animal nutrition, reproduction and breeding, and health and thereby contribute to sustainable food security while mitigating climate change by reducing GHG emissions. This is regarded as climate smart agriculture by the Food and Agriculture Organization of the United Nations (FAO).[11]

D.1. Environmentally friendly livestock management

To limit the global temperature increase to less than 2°C [2], the level at which the United Nations Framework Convention on Climate Change suggests that climate change impacts may become irreversible, the livestock industry has to address the twofold challenge of increasing production to provide global food security, while reducing total GHG emissions to protect the environment. Therefore, research is required to develop state of the art technologies and platforms that can simultaneously achieve these two objectives.

D.1.1. Meeting the increasing demand for animal source food

A 70% increase in the consumption of animal source food is expected by 2050 due to population growth, income increases and urbanization. Consequently, there will need to be manifold increases in livestock production. Current estimations are that livestock contributes approximately 14.5% (7.1 gigatonnes (Gt) CO_2-eq/year) of total anthropogenic GHG emissions.[12] Feed production and processing and fermentation of feed in the rumen of livestock

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[11] See http://www.fao.org/climatechange/climatesmart/en.

[12] Ibid.

are the two main sources of livestock GHG emissions, which account for 45% and 39% of livestock related emissions, respectively. Most of the GHG from livestock come from cattle (65%), and 31% of cattle emitted GHG is enteric methane. This is regarded as a loss of nutrients, and therefore improving feed digestion efficiencies will reduce enteric methane losses.

Other sources of livestock related GHG emissions are manure storage and processing (10%), expansion of pastures and feed crops into areas that were previously forested (9%), and fossil fuel consumption cutting across categories along the sector supply chain (20%). Short and medium term GHG mitigation goals and increases in livestock production can be achieved by adopting good farming practices to improve feed utilization efficiencies and individual and herd level productivity. For long term solutions, innovative research is needed to promote the development of more robust and productive animals that are adapted to harsh climates, resistant to diseases, and capable of utilizing poor quality forages and crop residues (see Fig. D.1). Research is also needed to improve the digestibility of crop residues without compromising grain yields and to develop grasses that grow in harsh climates while yielding a greater biomass with greater digestibility for animal consumption.

D.1.2. Good practices to reduce GHG emissions

According to the FAO, a 30% reduction in GHG emissions from livestock can be achieved if all producers in a community adopt climate smart agricultural practices, which have already been adopted by the top 10% of peer producers [1]. Research should be targeted at reducing GHG emissions by improving practices rather than by changing production systems that vary across livestock species and regions. GHG mitigation interventions must not increase energy expenditures in

FIG. D.1. Indigenous Kuri cattle in Chad are high milk producing and adapted to harsh environmental conditions.

other sectors. For example, by intensifying production systems and balancing forage rations with grain, the livestock industry in the United States of America and Western Europe produces 9–10 million t of protein while emitting roughly 0.6 Gt of CO_2-eq. In contrast, Latin America and the Caribbean produce an equal amount of protein after feeding livestock on poor quality pasture and forages with limited grain supplementation, and emit 1.3 Gt of CO_2-eq.

Research is needed, however, to establish whether livestock production intensification achieved by adding grains in feed will increase GHG emissions as a result of increased fossil fuel consumption and grain production. Additional environmental concerns may arise from excessive water utilization for more intensive livestock production. This demonstrates that thorough research is needed to design holistic approaches to increase livestock productivity while keeping GHG emissions as low as possible.

D.1.3. Win–win between production increases and mitigation interventions

In the management of any production system, profitability is often the decisive factor, and it is likely to drive the adoption of any GHG mitigation practices. Such technologies will therefore need to improve livestock production efficiency at individual animal and at herd levels. Most mitigation interventions do in fact provide benefits to both the environment and farm economics. For example, better quality feed and feed balancing not only lower enteric and manure emissions of GHG, but also help to increase productivity and income [2]. Improved breeding and animal health practices help to reduce breeding overheads (animals assigned for breeding that are not yet producing though they are consuming resources) and related emissions.

Dual purpose farming by smallholders with livestock that yield both meat and milk has been found to emit GHG emissions that are four times lower than those produced by specialized, separate beef and dairy farming [1]. Genetic characterization and marker assisted breeding and improved feeding can help improve meat quality and quantity from dairy animals. For example, an IAEA coordinated research project on genetic characterization of small ruminants for resistance to gastrointestinal parasites has identified sheep and goat breeds more resistant to gastrointestinal parasites in all 12 participating Member States (see Fig. D.2). Capacities such as DNA extraction, radiation hybrid panel mapping, ion proton based whole genome sequencing, single nucleotide polymorphism (SNP) microarray and genotyping human African trypanosmosis (HAT) have been transferred through technical cooperation projects and can be utilized for other genome related research, for example, for the characterization of livestock breeds for basal metabolic rates and better utilization of poor quality forages and crop residues and by-products.

FIG. D.2. Indigenous goats in Angola are tolerant to diseases and live on poor quality pasture.

D.2. Nuclear techniques to address GHG emissions

Nuclear techniques involving stable isotopes and radioisotopes and radiation are important tools in animal production and health research. The comparative advantage of nuclear techniques in livestock research and diagnostics is that they offer higher specificity and sensitivity than non-nuclear techniques [3]. The nuclear techniques described in the following subsections address GHG quantification and mitigation practices involving enteric fermentation, manure decomposition, feed and forage production, feed utilization efficiencies and pasture management.

D.2.1. Improving the digestibility of poor quality roughage

Improved digestibility in ruminants depends on diet balancing, which leads to improved fermentation in the rumen by microorganisms that produce volatile fatty acids (acetic acid, butyric acid and propionic acid) and thus provide nutrients to ruminants. An additional result of this process is the growth of a microbial mass, which meets a portion of the host ruminants' protein needs. During the process, purine bases that are present in the DNA and RNA of forages and microorganisms are degraded into purine derivatives (PD) such as xanthine, hypoxanthine, uric acid and allantoin, which are excreted in urine.

Urinary PD detection is a non-invasive in vivo technique for estimating microbial protein supply that is preferable to conventional techniques that are invasive. Carbon-14 tracers such as ^{14}C labelled uric acid and ^{14}C labelled allantoin have been used to develop models of the relationships between purine absorption and PD excretion in urine [4]. Infusion of ^{14}C labelled acetic and propionic acid is used to estimate volatile fatty acid production rates. Nitrogen-15 urea, ^{15}N ammonium bicarbonate and ^{15}N ammonium chloride can be used to study the microbial degradation of poor quality fibres, microbial mass, utilization of non-protein nitrogen, urea recycling, microbial protein synthesis and amino acid interconversions in rumen.

The rate of microbial protein synthesis is determined by ^{14}N, ^{32}P, ^{33}P or ^{35}S incorporation in the rumen microorganisms. Labelled minerals such as ^{76}As, ^{45}Ca, ^{67}Cu, ^{32}P and ^{75}Se are used to investigate mineral imbalances in farm animals. Cobalt-58 ethylene diamene tetraacetic acid, ^{104}Ru phenanthroline and ^{51}Cr labelled forages are used to determine passage rates. Carbon-13/carbon-14 labelled sodium bicarbonate infusion techniques are used to estimate CO_2 production in the rumen. These studies provide a basis for improving digestibility, which in turn increases feed conversion rates and energy utilization and reduces GHG emissions per unit product. Additionally, methane emission by ruminants can be estimated by isotope dilution using either ^{3}H or ^{14}C labelled methane.[13]

D.2.2. Genetic characterization of rumen microflora for improving ruminal digestibility

Rumen microbes play a vital role in the degradation of complex plant structures into nutrients required for their own growth and for the growth of host animals. The phylogenetic diversity of the microbial community in the rumen has been described by studying the small subunit ribosomal RNA or the corresponding genes. Technologies such as ^{32}P labelled oligonucleotide probes, denaturing gradient gel electrophoresis, fluorescence in situ hybridization and real time polymerase chain reaction (PCR) help to characterize and quantify rumen microbes and their dynamics. DNA based stable isotope probing holds considerable potential for linking microbial genetic information to biological functions. Metagenomic studies using next generation sequencing techniques help establish a complete landscape of the rumen microbial genome and plasmidome. This makes it possible to target novel domains, which are new genetic sequences that emerge in individual proteins as a result of their evolution, and their functional traits in ruminal digestibility [5].

[13] See http://www.fao.org/climatechange/climatesmart/en.

D.2.3. Breeding livestock for improved productivity while maintaining adaptability to local conditions

The identification of targeted genes and the characterization of indigenous and adapted livestock genomes will facilitate the identification of advantageous gene traits, such as those responsible for resistance to diseases (e.g. gastrointestinal parasites and trypanosomosis) or the ability to thrive under climate or nutritional stress. Isotope labelled DNA probes, dot blot hybridization techniques and radiation hybrid mapping, together with non-nuclear biotechnologies, such as PCR, and next generation sequencing for genetic characterization support marker assisted breeding of livestock for better productivity and adaptability.

D.2.4. Improving herd level productivity and reducing GHG emissions

A greater proportion of milk producing animals in a dairy herd results in reduced GHG emissions per unit of milk produced. Iodine-125 labelled progesterone has been used in radioimmunoassay (RIA) for the determination of progesterone in blood, milk and other body fluids and excreta [6]. Progesterone is a reproductive hormone, the determination of which aids the diagnosis of pregnancy, cyclicity and reproductive disorders in, for example, cows and buffaloes. Such diagnoses lead to improved reproductive efficiency, more animals calved and more milk produced per herd. RIA has also been developed for the analyses of other reproductive hormones, such as oestrogen, testosterone, follicle stimulating hormone, luteinizing hormone, equine chorionic gonadotropin and human chorionic gonadotropin.

Several molecules have been identified whose appearance in blood and other body fluids can be used for the early diagnosis of pregnancy and PCR and RIA can be used to detect the presence of such molecules. These molecules include pregnancy associated glycoprotein, early conception factor, interferon tau (IFN-tau) and IFN-tau stimulated genes. IFN-tau is particularly promising for early pregnancy diagnosis given its rapid appearance in maternal blood. Early pregnancy diagnosis is a very important tool for the management of herd level productivity by identifying animals that are not pregnant but are eligible for breeding. This can be used to reduce the proportion of non-productive animals and increase herd productivity.

D.2.5. Characterization and selection of tropical forages and development of forage agronomy

Mutation induction has been used widely to improve the yield and quality of forage crops. Qualitative improvements include greater digestibility (e.g. low lignin content) and greater nutrient content (e.g. improved protein composition), and these can be achieved without sacrificing yield. Plant mutation breeding has also been effective in developing fodder crops that are better adapted for harsh conditions (e.g. tolerance to waterlogging, drought, salinity and temperature extremes). Yields of these crops have therefore been improved because they can be grown in marginal regions.

The mixed crop–livestock production system aims at maximizing the production of animals and crops, including grains for human consumption, while minimizing the need for resources such as fertilizer, water and energy. Stable isotopes can be used to evaluate such improvements. Livestock make significant contributions to the sustainable intensification of a mixed farming system by providing manure that is used as fertilizer for soil, and draught power for cultivation. In such systems, the output of one process becomes the input of another, and there is minimum nutrient leakage to the environment, for example, in the form of GHG emissions.

Legumes and non-legumes when cropped together perform complementary functions that provide better quality and quantity of forages. Grass utilizes the nitrogen fixed into soil by legumes to produce higher biomass of higher quality. Nitrogen fixation and nitrogen transfer to other crops can only be measured accurately using the ^{15}N dilution technique, which requires labelling the soil with ^{15}N fertilizer (e.g. ^{15}N ammonium sulphate/^{15}N urea). Additionally, ^{33}P labelled fertilizer can be used to estimate the efficiency of phosphorus utilization in the production of leguminous forages.

D.2.6. Improved pasture management for sustainable animal agriculture and a sustainable environment

Silvopastoral systems, which integrate forestry with animal grazing, provide advantages over grass only pasture–livestock production systems.[14] Silvopasture not only minimizes GHG emissions and chemical contamination of soil and waterways, but also preserves biodiversity by minimizing the use of vehicles, fertilizers and herbicides (see Fig. D.3). Additionally, silvopasture helps to provide healthy soil with better water retention, additional feed in the form of protein rich leaves for more animals to graze, as well as shade to make the animals more comfortable in hot weather, which in turn encourages longer grazing and better nutrition, and thereby leads to increased milk and meat production per unit area of land as compared with cleared pasture alone. Double labelled water (^{2}H and ^{18}O) methods are used to estimate the energy expenditure of grazing animals.

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[14] See http://www.cam.ac.uk/research/news/sustainable-livestock-production-is-possible.

FIG. D.3. Silvopastoral systems of livestock production mitigate GHG emissions and chemical contamination of soil and waterways and preserve biodiversity.

D.2.7. Manure management and recycling through biogas technology

During storage and processing, the organic matter in manure is converted to methane and nitrogen that leads to nitrous oxide emissions. Increased emissions occur when manure is managed in liquid media, such as in deep lagoons or holding tanks. Stable ^{15}N labelled excreta can be used to monitor the fate of excreted nitrogen in the environment and to generate data regarding GHG emissions.

Biogas is a renewable energy source that can be generated from manure by anaerobic microbial digestion of its organic content. Its production reduces organic wastewater pollution that would otherwise consume oxygen and cause low oxygen levels in surface waters. Biogas effluents also conserve nitrogen and phosphorous in soil as nutrients for crop production. Additionally, the gas contains carbon that has been fixed in plants from atmospheric CO_2, which results in biogas production being carbon neutral, with no contributions to GHG emissions. According to the FAO, if all cattle manure were converted into biogas instead of being allowed to decompose, global GHG emissions could be reduced by 4% or 99 million t [1].

D.3. Conclusions

Nuclear techniques coupled with the use of molecular tools can be applied in innovative research and technology development to bring about sustainable increases in livestock production while reducing GHG emissions. Achieving these two objectives is becoming increasingly important as the human population and its demand for animal products expands, and as climate change mitigation becomes ever more necessary.

The Joint FAO/IAEA Programme of Nuclear Techniques in Food and Agriculture continues to develop and validate information and technology packages to contribute to GHG mitigation on a global scale. Such packages will enhance food security and improve livelihoods. To maximize their impact, it is important to raise awareness of the availability of these technologies and the practices described above, and to have broad stakeholder involvement (private sector, civil society, international organizations, research and academia) in addressing livestock production increases and their GHG contribution (or potential contribution).

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E. DIGITAL IMAGING AND TELERADIOLOGY: RECENT DEVELOPMENTS, TRENDS AND CHALLENGES

E.1. Technology and advantages of digital imaging

Until the end of the last century, the vast majority of medical imaging examinations used film as a medium for image capture, display and storage. However, the digital image revolution in medical diagnostic imaging began in the 1970s with the invention of the computed tomography (CT) scanner and the development of contemporary positron emission tomography (PET) scanners. The development of these nuclear imaging techniques was followed in the 1980s by magnetic resonance imaging (MRI), a non-nuclear imaging technique, and the invention of digital X ray acquisition systems (such as computed radiography and digital radiography) in the 1990s. Modern medical imaging techniques such as CT, PET and MRI generate dramatically greater amounts of diagnostic information than their predecessors, which have given rise to the need to manage this information effectively and efficiently. This growing need has driven the widespread adoption of digital image management technologies, which are now the preferred method for image capture, display and storage owing to their capacity to make modern nuclear and non-nuclear imaging techniques more cost effective and accessible.

There are a number of advantages inherent in digital capture, storage and display as compared with alternatives involving film that make such benefits possible (see Table E.1). Though the initial cost of digital equipment is higher than for conventional systems, in the long term the digital technology would bring overall cost savings through reduced running costs, as it does not require chemicals, films, film handling and film storage. Despite these advantages, implementing fully digital medical imaging systems, including reporting, archiving, and image distribution, is a complex effort (see Fig. E.1). Such systems are not a turnkey, one size fits all, technological solution, as they must be customized for different diagnostic activities and end users and require significant training for operation.

TABLE E.1. ADVANTAGES OF DIGITAL RADIOLOGY OVER CONVENTIONAL FILM BASED RADIOLOGY

1	Efficient information dissemination and increased access to images
2	Significantly better dynamic range of digital image acquisition systems to capture more, and more diverse, anatomical structures in individual images
3	Improved reliability, error free retrieval of images without loss of diagnostic information
4	Ease of use
5	Potential for multimodality, composite imaging
6	Retention of dynamic diagnostic information as a series of digital images
7	Simultaneous transmission and display of images to multiple geographical areas
8	Image manipulation and processing, feature extraction and enhancement
9	Ease of interaction between specialists (e.g. radiologists with referring physicians)
10	Expertise in subspecialties of diagnostic imaging can be widely disseminated
11	Studies are available to authorized viewers immediately after image acquisition
12	Examination sequencing and tailoring and integration of diagnostic data are possible
13	Elimination of environmental problems (e.g. discarded film and chemical waste)

Source: IAEA Human Health Series No. 28, Worldwide Implementation of Digital Imaging in Radiology [1].

FIG. E.1. Typical workflow of a digital imaging chain (courtesy of Carestream).

E.2. Moving from analogue to digital systems

E.2.1. General challenges

Even though the overall impact of digital imaging is generally very positive, the transition from conventional (screen film) radiology to digital imaging is a major change that must be effectively implemented. Traditional film based methods have been used for a century and cannot easily be abandoned. Furthermore, the required capital cost, including for human capital development and the need to move towards digital technology quickly presents challenges for some users. Communication strategies and an understanding of the principles of change management are essential in this [2]. This is a particular challenge as the time and investment required to carry out such transitions varies widely and is heavily influenced by the circumstances at the start of the process.

Though such steps can minimize the difficulties caused by these changes, there will often be a period of adjustment during which the transition may be confusing, disruptive or even dysfunctional. Almost universally, however, after the initial period of use of digital imaging, users come to recognize and appreciate the advantages of digital imaging over film based imaging.

E.2.2. Implementation and specific challenges for medical personnel

The radiological staff (radiologists, radiographers, medical physicists and assistance personnel) should be part of a wider staff consulting group that provides subject matter expertise to the project. This will allow all radiological staff members the opportunity to comment on, and contribute to, plans and drawings in process. Planning and providing the necessary new training, including basic computer literacy, should be a part of the implementation plan. As the maximum speed of any transition is determined by the ability of the staff to adopt change, an effective and ongoing staff development and training programme is one of the most important components of a digital imaging project.

The end users of any radiology service are the physicians who refer patients. The absence of film may disrupt the work of some physicians, and the introduction of digital imaging, therefore, may initially affect their clinical service delivery. Physicians need to be trained to use computer systems for image distribution, and they will act as a valuable source of feedback, both positive and negative, for the effectiveness of digital imaging distribution outside the area of radiology. At the project planning stage, it should be clear how existing users will be served during and after the transition to digital imaging. The planning should also identify those physicians and departments that will have particular requirements for the medical imaging service (e.g. cardiology and orthopaedics). Close interaction between these individuals and the digital imaging implementation team is essential. It is vitally important to make it clear that the service is developed to provide the most benefit to them as users of the radiology services.

If a facility has an in-house or local IT department or section, that group should be engaged early in preparing the transition to digital imaging. It is, however, crucial that the IT group understands that solutions must follow standards and practices that are well defined worldwide within the digital imaging community. This may require the development of a memorandum of understanding between the project steering committee and the IT group to define the required inputs. If free software and off the shelf hardware become part of the solution, the local IT group should prepare those components well in advance of the planned installation of the image acquisition equipment.

E.3. Teleradiology

One of the principal advantages of digital imaging technology is that, through teleradiology applications, it has the ability to make expert diagnostic opinion available irrespective of the distance between the place where the image is acquired and the location of the expert. Teleradiology can be defined in many ways, but in general terms it can be defined as the transmission of a set of full resolution, full integrity images to a centre distant from where the images were acquired for the purposes of primary diagnostic interpretation or expert secondary consultation. Such technologies are already widely used in developed countries, and while some developing countries are also using teleradiology, its implementation in these countries is still limited [3, 4].

Teleradiology can be used locally (e.g. in the same facility), between buildings in a shared complex or a single city, or between health facilities anywhere in the world. It offers alternatives to traditional imaging interpretation approaches, which require on-site staff capable of radiological interpretation. Teleradiology can:

- Improve access to expert medical opinion, either for primary or secondary interpretation;
- Provide access to medical image reporting for underserviced centres;
- Support patient consultations and inform patient treatment decisions;
- Provide access to image interpretation for remote regions;
- Shift reporting to provide timely interpretation after normal working hours;
- Balance reporting workloads between centres with differing levels of staff to ensure timely turnaround of reports.

E.3.1. Technology

Teleradiology has evolved to adopt modern technology and offer different uses [5]. When used with a picture archiving and communication system that is remotely accessible, or a centralized archive, teleradiology is indistinguishable from any other form of remote access. The Internet and web based thin client technology (in which a computer requires a connection with a server to fully function) are typically used. Additional use cases that are now possible due to these advances include part or full time interpretation work from home, load balancing of interpretation work between different sites, including across time zones, and outsourcing of emergency or final interpretation work to third parties who can provide additional expertise.

From a technical point of view, it is not a problem to transfer any image to most locations across the world, but effective teleradiology solutions also require proper workflows to handle large numbers of teleradiology cases in an efficient way. Images have a wide range of sizes from a few megabytes to hundreds of megabytes, and the transfer of large image sets may be extremely slow and therefore impractical. The available network, then, is a critical component of teleradiology applications that requires appropriate planning and resources, and that can be an impediment to the adoption of the technology.

The type of network will depend on local availability, and the required bandwidth will depend on the image size and volume to be transferred. However, the extension of local systems to provide remote access may be limited by network performance issues, especially in rural areas, as well as in areas with security issues, particularly due to the need to provide external users with authenticated credentials and to control their access.

Teleradiology equipment, including all image acquisition equipment, should be compliant with the corresponding International Organization for Standardization designated standards for digital imaging and communications in medicine for communication with workstations, telecommunication devices and image storage. Some locations have no means (or plans) for connecting to referring physicians or teleradiology reading services, while other locations can utilize internal and external networks as a part of the medical imaging chain.

Finally, as there may now be a considerable distance between where the clinical images are generated and where these are reviewed and reported, it is important that both sites have a clear understanding and agreement on the responsibilities and the access privilege policies which are to be followed to ensure that patient data remain confidential.

E.3.2. Examples of implementation

Teleradiology is distinct from the transmission of a small number of limited quality images that are sent primarily for the purposes of discussion or demonstration. An example of the latter is the use of non-medical communication technologies such as mobile telephony or email. Most mobile phones and other forms of portable computing currently in use have limited memory size, networking and processor speed, and are therefore unlikely to be used for primary diagnostic interpretation and reporting. However, this situation is changing rapidly, and it can be expected that in the near future such devices will become increasingly important in the sending and reviewing of medical images (see Fig. E.2).

One of the most common examples of teleradiology implementation involves the connection of peripheral hospitals in a country or region with a central institution. This provides the opportunity to physicians in rural areas, who might not have experience in interpreting images, to seek primary diagnostic interpretation support from specialized doctors in larger, academic or specialized hospitals. This may be done to provide accurate diagnosis and thus more effective treatment locally or, if required, to identify the need to transfer patients to a facility with a higher level of care. The direct beneficiaries of such teleradiology projects are the related hospital staff and, more importantly, the patients whose images are subjected to expert reading by a radiologist [4].

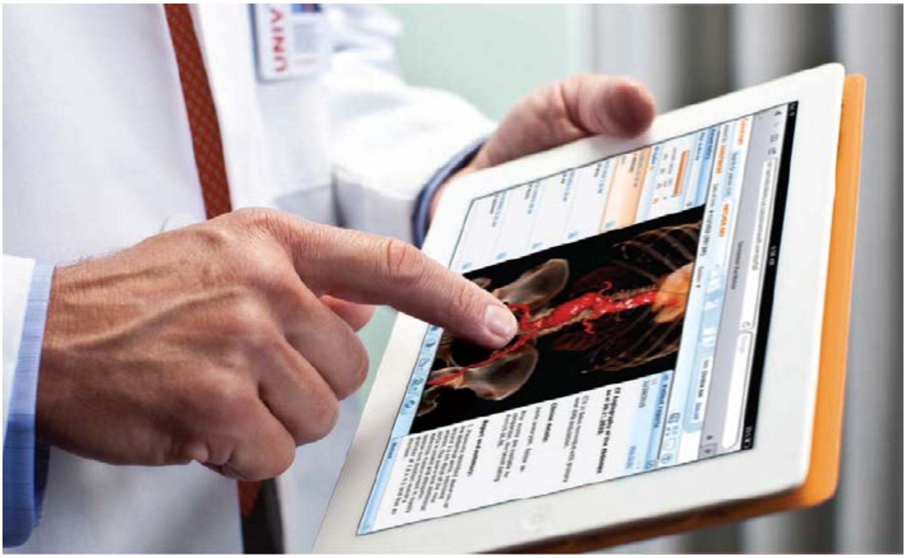

FIG. E.2. Display of CT image on a tablet PC (courtesy of Carestream).

FIG. E.3. Digital mammography workstation.

Screening mammography has been proven to be a powerful tool for the early detection of breast cancer. Several studies have demonstrated an increase in the detection rate of breast cancer with the adoption of the double reading method (which provides two expert readings to ensure a more reliable diagnosis) and with the readers' cumulative experience in reviewing images [6]. In an organized teleradiology (telemammography) framework, the centres that participate in a screening programme would benefit significantly if the independent second reading of the mammograms were done by expert radiologists in a central breast unit (see Fig. E.3). These readers, due to the large number of images they read, would have advanced skills and experience in mammography reading and could improve the effectiveness of the screening programme.

E.4. Conclusions

Given the advantages and possibilities offered by digital imaging, there is an ever increasing move away from film based examinations in favour of digital acquisition, processing and display that can increase the efficiency and accessibility of important nuclear and non-nuclear imaging techniques. This shift is currently more pronounced in developed countries, although developing countries are also beginning to benefit and could further benefit by more widely embracing digital technology for radiological examinations.

Teleradiology can become a practical and effective method to address the uneven geographical distribution and local shortages of imaging specialists. The increasing role of technology may help to alleviate staff shortages, although new roles in technical infrastructure support will be necessary. The challenge for developing countries is to find a methodology that is appropriate to their needs and circumstances to move effectively from conventional film processing and storage to digital acquisition and display.

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F. RADIATION TECHNOLOGY FOR WASTEWATER AND BIOSOLIDS TREATMENT: SOLUTIONS FOR ENVIRONMENTAL PROTECTION

F.1. A role for radiation technology in environmental protection

The continued urbanization and industrialization of societies across the world is a leading factor in the contamination of already depleted freshwater supplies and the generation of vast amounts of municipal sewage sludge. The emergence of organic contaminants such as pharmaceuticals, textile dyes, insecticides and endocrine disruptors in wastewater and sludge has further aggravated the problem as such chemicals, even at trace levels, may profoundly affect aquatic life, land animals and humans. The treatment of industrial and wastewater effluent and sludge helps to conserve water resources and improve soil conditions.

The continuing advances in wastewater treatment technology and increasingly stringent wastewater discharge requirements ensure that most treated wastewater effluents are safe for discharge. However, the treatment is insufficient to enable the reuse of water or the use of sludge, and therefore alternative applications should be investigated. Radiation techniques using gamma and electron beam (EB) technologies have been successfully deployed to demonstrate the treatment of industrial textile dye wastewater and sanitization of sewage sludge for agricultural applications.

Radiation technology for the treatment of different organic pollutants has not yet been widely adopted for full scale use, but its usefulness and efficiency have been demonstrated at various scales of operation, and the technology has great potential for dealing with emerging wastewater and sludge treatment challenges. As industrial effluents and wastes are generally not mixed and instead are required to be treated at the source, such technologies could be configured to suit differing waste treatment needs.

F.2. Current issues in wastewater and sludge treatment for reuse

As water shortages have intensified, worldwide interest in reusing water has increased. At the same time, however, potential microbial and chemical water contamination, especially from new trace contaminants, has become a growing source of concern. The development of cost effective and reliable water reclamation technologies is therefore vital to the successful implementation of water reuse projects.

Advanced treatment technologies, such as radiation technologies and their combinations with conventional processes, are now being tested for the production of high quality water for indirect potable reuse, for example recycled water that is specially treated before undergoing conventional water treatment for potable use. Such technologies are expected to become the predominant treatment technologies in the near future.

The growing trend towards increasingly stringent wastewater discharge standards has been beneficial for the environment, but these standards have also led to an increase in the generation of sewage sludge. A number of options to dispose of sewage sludge, including incineration, disposing of it in landfills, or using it as fertilizer or soil nutrient are currently available, though the composition of the sludge can limit these choices.

In future, wastewater treatment plants are expected to be high value resource recovery operations rather than locations for the treatment and subsequent disposal of municipal wastes. However, for this to become a reality, it is critical to identify technologies that can cost effectively disinfect and stabilize municipal biosolids. In this regard, increased attention is being devoted to the production of high quality biosolids that present no public health or environmental risk and that can be used beneficially.

F.3. Present status of radiation technology applications in wastewater and sludge treatment

F.3.1. Electron beam treatment of textile dyeing wastewater

The textile dyeing and dye production industry accounts for nearly 20% of global industrial water pollution. Over 700 million t of dyes are produced worldwide each year, and the dyeing processes are extremely water intensive, requiring approximately 80 000 m^3 of water for every tonne of finished textile. The effluent water from the industry has a high chemical oxygen demand, which is indicative of high concentrations of organic pollutants and low biodegradability due to salinity and the presence of a wide range of chemicals.

The conventional biological treatment process for the treatment of dye wastewater, besides requiring a long treatment time, cannot degrade synthetic dyes owing to their complex chemical structures. High energy electrons from EB accelerators have been proven to degrade these complex dyes effectively into simpler molecules to facilitate their subsequent biodegradation. The process is easy to integrate with the existing biological treatment process. The presence of solid particles of up to 3% clay has been shown to have no adverse impacts on the destruction of the chemicals. Solutions that contain strongly light absorbing compounds do not decrease the efficacy of the process, and no additional chemicals are needed for the process. The level of degradation achieved renders the by-products vulnerable to subsequent biological treatment processes, thereby minimizing treatment costs. Accelerators using up to 400 kW of power have been shown to be extremely reliable and rugged and approach ≥99% operational availability. The accelerators are totally automated for on-site or remote site operation with a lifetime in excess of 30 years.

The EB facility at the Daegu Dyeing Industrial Complex, in the Republic of Korea, has demonstrated the effectiveness of EB technology for treating up to 10 000 m^3 of textile dye wastewater per day at a dose of 1 kGy and an economic cost of US $0.30/$m^3$ [1]. The cost for such a high powered accelerator is around US $2 million for the accelerator and its installation, while piping, other equipment and construction works cost approximately US $1 million (see Fig. F.1). At present, this is the only facility of its kind in the world, and the stated initial costs are an impediment to the establishment of additional facilities. The increasing costs of environmental regulations and remediation in some States are leading many textile dyeing companies to relocate to States where environmental regulations are less stringent, which highlights the need to increase the capabilities and cost effectiveness of such technologies to encourage wider adoption.

FIG. F.1. Treatment of wastewater using an electron beam accelerator (courtesy of EB Tech).

F.3.2. Sludge treatment using high energy radiation

High energy radiation is an effective and efficient method for deactivating pathogenic bacteria, and the technology is already used on a large scale worldwide to sterilize medical equipment. Based on a similar concept, the use of radiation technology to sanitize sewage sludge has been investigated in many States. Sanitized sludge has been found to be an effective carrier for useful bacteria such as rhizobium, which helps to fix nitrogen in soil, and has been demonstrated to be an excellent enriched manure in large scale trials [2]. Biosolids, therefore, can replace less environmentally friendly chemical fertilizers.

The successful and continuous operation since 1992 of the Sludge Hygienization Research Irradiator (SHRI) facility in Vadodara, India, has shown that irradiating sewage sludge, containing about 5% solid content, with ^{60}Co gamma radiation at a 3 kGy dose can deactivate 99.99% of pathogenic bacteria. The technology is easy to integrate with existing sewage treatment plants. In addition, the organic manure by-product resulting from the operation of the SHRI facility has been effectively used by agriculturists and horticulturists, who have demonstrated enhanced productivity. However, the high throughputs needed for the treatment process and need for periodic replenishment with very large quantities of ^{60}Co have limited the spread of this potentially useful technology.

In recent years, high energy EB technology has been shown to be highly effective as a disinfecting technology resulting in significant reductions of a variety of target bacterial and viral pathogens. The results indicate that doses 8–15 kGy destroyed significant numbers of bacterial, viral and protozoan pathogens. The engineering specifications of a high energy EB treatment system capable of delivering the required doses have been developed, modelled and empirically validated. Monte Carlo simulations (a computerized mathematical technique that helps to account for risk in quantitative analysis and decision making) and empirical tests have confirmed that it is technically feasible and cost effective to deliver uniform EB doses to biosolid streams of varying concentrations of solids and water quality at approximately 1500 m^3/day [3]. In addition to the technical feasibility, preliminary cost estimate analyses indicate that high energy EB based disinfection can be extremely cost effective compared with some contemporary treatments such as digestion by thermophilic bacteria for heat drying, composting and lime stabilization.

Furthermore, synergistic disinfection of pathogens has been achieved when EB irradiation was coupled with chemical oxidants such as chlorine dioxide and ferrate. The combination of EB irradiation and ferrate treatment has been found to be effective in disinfecting microbial pathogens, destroying oestrogenic activity, and stabilizing biosolids. It costs approximately US $70 per dry tonne to combine an EB irradiator with ferrate to produce high quality biosolids, which is significantly lower than other contemporary technologies. The ability to disinfect and stabilize municipal biosolids by combining EB irradiation with chemical oxidants opens up a number of opportunities for reusing biosolids and for resource recovery.

F.4. Radiation technology for addressing emerging water pollutants

In the area of water treatment, there is growing concern over chemicals known as endocrine disruptors (chemicals that can cause disease by interfering with hormone systems), as well as personal care products and pharmaceuticals, as they cannot be completely removed or destroyed by conventional treatment processes. Trace amounts of these chemicals, which are hazardous to aquatic animals at 1 ng/dm^3, are difficult to treat with existing methods. Moreover, their concentrations in freshwater environments that tend to receive wastewater discharge have increased gradually because of population growth and the worldwide diversification of pharmaceuticals now in use.

Such compounds can be treated using emerging techniques involving free radicals in advanced oxidation processes. Ionizing radiation methods have reportedly been effective in decomposing persistent organic pollutants such as dioxin, polychlorinated biphenyls and endocrine disruptors (see Ref. [4] and references therein). Gamma ray irradiation has been shown to degrade endocrine disruptors and their irradiation products in wastewater at a dose of 200 Gy. The estimated cost of a treatment plant using an EB irradiator for this purpose is US \$0.17/m^3. Experiments conducted on pharmaceuticals have also shown that drugs like diclofenac that have been shown to be harmful to freshwater species can be efficiently removed from water using irradiation technology [5].

In 2010, the Korea Atomic Energy Research Institute (KAERI) developed a mobile EB accelerator that has been used to conduct a field study on the treatment of many such chemicals contained in sewage effluent (see Fig. F.2). The major antibiotics and endocrine disruptors with initial concentrations of 0.5 mg/L were decomposed completely by an irradiation dose of less than 1.5 kGy, and coliform bacteria and other microorganisms were also sterilized by the same irradiation dose. The study showed that toxicity arising from antibiotics in algae was reduced by exposure to irradiation. The mobile EB accelerator was designed to serve as a demonstration device that can easily be taken to a variety of industrial installations to demonstrate the potential of EB accelerators for the cost effective treatment of different types of wastewaters, with the goal of encouraging further adoption of the technology. The results obtained from this study played an important role in earning a New Excellent Technology certification from the Korean Ministry of Environment on advanced treatment of sewage effluent by radiation [6].

FIG. F.2. A mobile electron beam accelerator installed in sewage treatment plant (courtesy of KAERI).

F.5. Future research needs and challenges

While the processes related to applications of radiation technologies for the treatment of wastewater, sludge and other pollutants are fairly well understood and established, the emerging challenges that are likely to affect industry in the coming years, and the potential benefits of utilizing new applications to respond to these challenges, suggest that further work should be carried out in developing these applications. These emerging challenges represent future opportunities to support the growth of radiation technology applications in industry for environmental remediation.

One such challenge is the presence of emerging chemicals of concern in wastewater and sludge, which demands comprehensive and consistent analysis at municipal wastewater treatment plants. These capacities are needed to assess whether toxic organic compounds are present in wastewater and sludge at concentrations that pose a risk to human and animal health and to the environment, and subsequently to evaluate and ensure the effectiveness of irradiation in treating wastewater.

The irradiation of tertiary effluents to ensure maximum effluent quality before discharge into the environment presents another challenge, and this requires empirical data on disinfection levels following the treatment of high volumes of wastewaters with EB accelerators. The availability of mobile EB accelerators also offers new opportunities to provide clean, disinfected water for non-potable purposes in the case of natural disasters or similar emergencies that can affect water services, but further studies are needed for such applications. This could be particularly relevant in the context of the increasing frequency and severity of natural disasters associated with climate change.

F.6. Conclusions

Radiation techniques have the potential to address a variety of environmental, public health and resource needs and challenges when used to treat wastewater and sewage sludge. They have successfully demonstrated their effectiveness in the treatment of industrial textile dye wastewater and in the sanitization of sewage sludge to provide additional resources for agricultural applications. Recent studies have demonstrated the potential of radiation initiated degradation of emerging organic compounds of concern to transform them into less harmful substances or to reduce their concentrations to within permissible ranges. The usefulness and efficiency of radiation technology for the treatment of a variety of organic pollutants have been adequately demonstrated at various scales of operation.

The development of mobile EB facilities has enabled radiation technologists to demonstrate such processes to end users under actual working conditions, and mobile facilities may also be used to respond to natural disasters and other emergencies. Furthermore, applications such as those above have the potential to support the reuse of treated wastewater for urban irrigation and industrial purposes, which would help to respond to increasing water scarcity worldwide due to growing human demand and climate change. With further research and development, radiation technologies such as these can prove themselves to be of great value to humankind.

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G. ADDRESSING HARMFUL ALGAL BLOOMS IN A CHANGING MARINE ENVIRONMENT

G.1. Nuclear technologies for tracking marine biotoxins in seafood and the environment

G.1.1. The impact of harmful algal bloom toxins on seafood trade

Aquatic animal products are important to many developing countries as a supply of animal protein and a commodity for trade. Global demand for seafood has been increasing, boosting both imports and local production. Due to the stagnating populations of capture fisheries, aquaculture now contributes more than 50% of total seafood supply worldwide. Seafood is the most highly traded food commodity internationally and exports of seafood from developing countries exceed the total value of coffee, cocoa, tea, tobacco, meat and rice combined [1]. In addition, developing countries represent approximately 50% of global seafood exports [2].

Exporters' ability to adhere to the regulatory requirements of importing States has become a major impediment to market access in the fisheries sector [1]. Imports of seafood such as oysters, clams, scallops and mussels are subject to labelling, traceability and official certification to ensure quality and safety. Local regulatory authorities in many States have placed particular emphasis on establishing and enforcing regulatory limits and criteria for marine biotoxins.

Marine biotoxins are produced by certain microscopic marine algae that can, in certain conditions, bloom and reach high densities, forming harmful algal blooms (HABs), also referred to as 'red tides'. Through feeding, fish and shellfish may accumulate these biotoxins and become dangerous for human consumption. Seafood may hence be deadly even if waters are apparently clear and seemingly free of an HAB. Toxic and non-toxic seafood has the same taste and appearance, and HAB toxins are not destroyed by cooking or freezing (see Fig. G.1).

HAB toxins are responsible for massive economic losses to the shellfish industry through closures of harvesting facilities that are imposed when toxins in shellfish exceed regulatory levels. When a regulatory programme is not in place, the lack of seafood toxin controls represents a risk for the consumers and an impediment for exports. Toxic outbreaks can also cause social alarm (including broader impacts from uninformed consumers avoiding all seafood), adversely affecting the tourism industry and encouraging fish imports from controlled areas to the detriment of local fisheries. Nuclear techniques can be used to identify and measure HAB toxins in seafood, and to study the impact of environmental and

FIG. G.1. HAB toxins may accumulate in edible marine organisms such as mussels or fish. Seafood products for trade in Chile (left) and a fish market in Polynesia (right).

climatic changes on the dominance of HAB species, their distribution patterns, and the probable frequency of future outbreaks.

Following requests made by Member States to address the impact of HABs, the IAEA has been, through the Technical Cooperation Programme, developing and strengthening national and regional capacities and capabilities in algal toxin detection in seafood and HAB management to promote sustainable safe seafood supply.

G.1.2. A newly validated nuclear based method for analysing algal toxins

The nuclear based receptor binding assay (RBA) is a specific and sensitive method developed for the analysis of algal toxins associated with paralytic shellfish poisoning (PSP), diarrhetic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP) and ciguatera [3, 4]. RBA is based on the ability of a toxin occurring in a sample extract to compete with a tritium radiolabelled biotoxin (e.g. tritiated saxitoxin or tritiated brevetoxin) for binding to their pharmacological target proteins (i.e. receptors). Quantification of the binding can be carried out using a liquid scintillation counter, which measures beta irradiation from radioisotopes, either in traditional vials, or using a microplate reader.

RBA is a key application of nuclear technologies that can circumvent problems related to the conventional method widely used to detect toxins, which is the mouse bioassay. RBA provides an estimate of the integrated toxic potency of a sample, is highly specific and has a very low detection limit, which enables this technique to provide regulatory authorities and producers with important early warning information regarding an HAB.

The high throughput of the microplate format of RBA minimizes the use of reagents and the production of radioactive wastes (see Fig. G.2). Radioactive material used for this method is in exempt quantities (e.g. tritium radiolabelled toxin, approximately 5–37 kBq per plate) and is considered safe for transportation, laboratory radiation protection programmes and waste disposal. The instructions on the use of the RBA are easy to follow, and procedures have been detailed in IAEA-TECDOC-1729, Detection of Harmful Algal Toxins Using the Radioligand Receptor Binding Assay: A Manual of Methods [3]. The publication was produced in collaboration with the National Oceanic and Atmospheric Administration (NOAA) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a complement to IOC Manuals and Guides Series No. 59 on HABs [6].

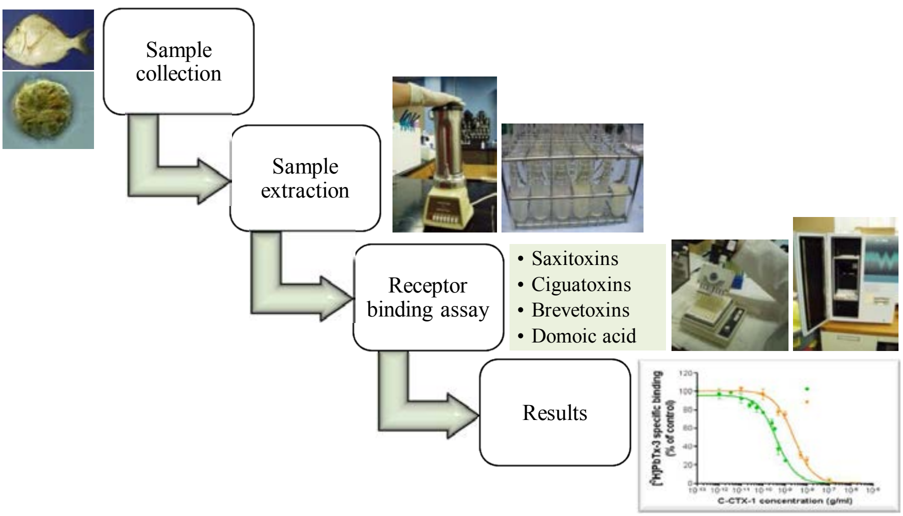

FIG. G.2. Seafood samples are subjected to a chemical procedure of extraction and tested for their toxin level using the radioligand receptor binding assay (modified from Ref. [5]).

With the support of the IAEA, this method was submitted by the NOAA to AOAC International, which sets global standards for chemical analysis. RBA is now recognized as an AOAC First Action Official Method for PSP measurement in shellfish [7]. Nine laboratories from six Member States (Australia, Chile, Italy, New Zealand, Philippines, Thailand and United States of America), including the Philippine Nuclear Research Institute, an IAEA Collaborating Centre, participated in the interlaboratory comparison exercises that led to this recognition. In line with this achievement, efforts are being made by the IAEA and its Member States to develop similar interlaboratory exercises for other toxins, such as those responsible for DSP, NSP and ciguatera, which can be effectively and efficiently detected using RBA.

Further actions at the national and international levels are being taken to promote the implementation of RBA by regulatory bodies. For example, RBA has been submitted to the United States Interstate Shellfish Sanitation Conference Laboratory Methods Review Committee, which promotes shellfish sanitation through the cooperation of State and Federal control agencies, the shellfish industry and the academic community. It is currently under consideration as an Approved Limited Use Method by the United States National Shellfish Sanitation Program. In addition, following the recommendation of the IAEA Advisory Committee on HABs of the interregional technical cooperation project INT7017, a proficiency testing via the European Union Reference Laboratory for Marine Biotoxins, following EU regulations, is being considered.

G.2. Nuclear technologies to study harmful algal blooms in relation to past and present environmental and climatic changes

Growth, toxicity and geographical distributions of HAB species are affected by local and global climate and environmental changes. Nutrient over-enrichment, also known as eutrophication, of coastal and inland waters is a direct consequence of food and energy production, and the concomitant production of waste and sewage, for a growing human population. Atmospheric deposition of nitrogen (in the form of nitrogen oxide in acid rain) is also a source of nutrient over-enrichment.

The overloading of organic nutrients or altered nutrient ratios in marine ecosystems often results in an increased algal biomass in water bodies, and has been correlated with numerous blooms of cyanobacteria and dinoflagellates [8]. Eutrophication is now considered as one of the largest global pollution problems [9]. In this context, radionuclides and stable isotopes can be used to increase understanding of the carbon and nitrogen cycle, and more generally, the influence of anthropogenic activities in locations where HABs occur.

Some of the most harmful toxin producing dinoflagellates (e.g. *Gymnodinium* and *Pyrodinium*) can produce cysts that become buried in marine sediment — a resting stage that may fossilize. Nuclear techniques can be used to extract valuable information from sediment cores containing such fossils to reveal the impact of environmental and climatic changes on HAB species dominance and distribution. These techniques include the application of $^{210}Pb/^{210}Po$ derived sedimentation rates and dating. The reconstruction of palaeoclimatological conditions is also possible using, in this case, stable isotopic ratios as proxies, and allows a better understanding of environmental conditions prevailing when cysts were produced.

Stable isotopic tools include, for example, the determination of $^{12}C/^{13}C$, $^{16}O/^{18}O$ or $^{14}N/^{15}N$ ratios. The latter ratio is frequently used as a recorder of changes in productivity, as well as of nutrient levels in the water column and the origin of nitrogen compounds. The relation between these factors and the occurrence and abundance of cysts in the sediment contribute to an understanding of the role of abiotic parameters in the occurrence of HABs.

These kinds of dataset are rare but essential to determine whether an HAB species has been recently introduced in a new area, and whether blooms of an HAB species are increasing in frequency, intensity and geographical extension, or are just undergoing normal decadal fluctuations. This information is important to understand and project changes in HAB events, to use the adequate analytical tools for detecting the toxins effectively and efficiently at an early stage, and to adapt strategies for the management of ecosystem services and seafood safety.

Over the past decade, climate change and eutrophication have also been implicated in the rising toxicity of HABs in freshwater habitats, including lakes and estuaries. Algae naturally occur in freshwater, where, under favourable conditions, they can multiply as rapidly as their marine equivalents. Among freshwater algal species that can be found in lakes or estuaries, cyanobacteria produce potent toxins threatening aquatic organisms, ecosystem health, and human and livestock drinking water safety (see Fig. G.3). Such toxins have been known to kill hundreds of livestock animals at a time. Genera of cyanobacteria that produce saxitoxin have been observed in many lakes around the world, and this toxin has been detected at low levels in water treatment intake and throughout water treatment processes in New Zealand [10]. As with marine HAB toxins, RBA appears to be a promising tool that could be easily adapted for monitoring freshwater HAB toxins. This is a potential future area for the application of RBA.

FIG. G.3. Land and aquatic animals poisoned by freshwater HABs (courtesy of the Woods Hole Oceanographic Institution).

G.3. Conclusions

The severity of HAB impacts on marine ecosystems and the vital sources of food they provide are expected to increase in the future. These impacts will be particularly felt in the developing world, and will include a number of small island developing States that depend heavily on seafood as their primary source of protein. Nuclear techniques such as RBA are proven tools for monitoring algal toxins in seafood and the environment efficiently, and for improving knowledge on the impact of climatic variability on HABs and the marine ecosystem.

Regional and interregional approaches are essential to address the transboundary nature of this major environmental challenge that is affecting the environment, public health, and socioeconomic welfare, and to enhance the multinational cooperation that is required to improve the efficiency of the management of HABs in the context of global climate and environmental changes. The IAEA, together with the IOC and the United Nations Environment Programme, in the framework of the Global Partnership on Nutrient Management of the IOC's Global Ecology and Oceanography of Harmful Algal Blooms programme and the IOC Intergovernmental Panel on Harmful Alga Blooms, is carrying out work to develop an early warning system and to improve forecasts and assessments of the impacts of environmental and global changes on HABs. All of these measures are essential to ensure the sustainable management of marine ecosystem services and seafood safety.

In response to the growing interest expressed by Member States in mitigating and managing HAB events and their impacts, the IAEA has expanded and accelerated its activities to address the effects of HABs on the environment and on seafood safety. RBA technology and expertise has been transferred to several Member States from the Latin America, Asia and the Pacific, and Africa regions, and these efforts will be strengthened further in the years to come.

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Annex I

NUCLEAR POWER AND CLIMATE CHANGE

I–1. Introduction

Global climate change has dominated international environmental and energy agendas over the past two decades. Increasing scientific evidence indicates that anthropogenic emissions of greenhouse gases (GHGs), especially carbon dioxide (CO_2) emissions from burning fossil fuels in the energy sector, lead to changes in the atmosphere that alter the Earth's climate. The impacts of climate change above the threshold value of a 2°C increase in the global mean annual temperature above the pre-industrial level are widely believed to be largely negative in key sectors such as ecosystems, agriculture, water supply and human health in most regions of the world. The twin challenge for the world society will be to increase energy supply to support the socioeconomic development of an increasing global population and to mitigate GHG emissions. This annex presents the results of the most recent scientific assessment of climate change, the status of international negotiations to manage climate change and the potential contribution of nuclear energy to resolving the energy–climate challenge, and summarizes the main conclusions.

I–2. Climate change science

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) adopted a new approach to project anthropogenic climate change for the next few centuries [I–1]. Abandoning the traditional pathway tracking changes from GHG emissions through atmospheric concentrations and radiative forcing[1] to climate attributes such as temperature and precipitation, the new projections are based on alternative assumptions about radiative forcing values for the year 2100.

These new scenarios include four representative concentration pathways (RCPs) for exploring the near and long term climate change implications of different pathways of anthropogenic emissions of all GHGs, aerosols and other climate drivers. The four RCPs depict approximate total radiative forcing values

[1] Radiative forcing is the change in energy flux caused by drivers (natural and anthropogenic substances and processes that alter the Earth's energy budget). It is quantified in watts per square metre (W/m^2), and it is calculated at the tropopause or at the top of the atmosphere.

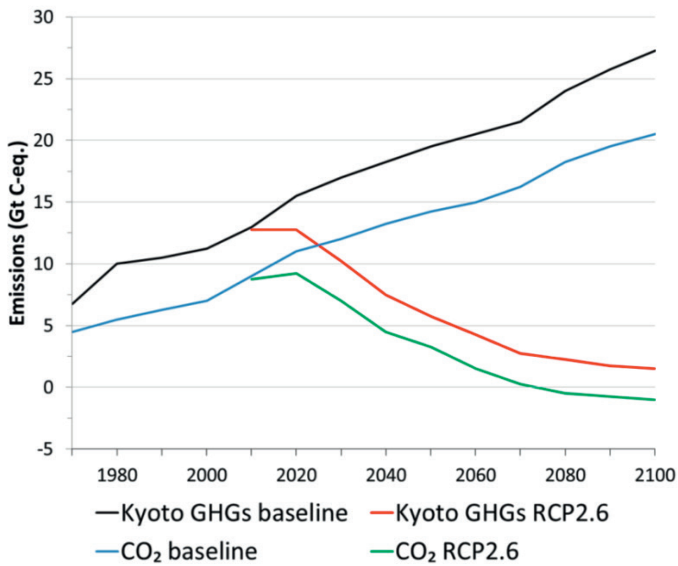
for the year 2100 relative to 1750 in the range of 2.6–8.5 W/m^2. RCP2.6 assumes strong GHG mitigation actions. Radiative forcing along this pathway peaks and declines during the twenty-first century, and leads to a low forcing level of 2.6 W/m^2 by 2100. For RCP4.5, radiative forcing stabilizes by 2100. In contrast, the two high concentration pathways (RCP6.0 and RCP8.5) entail continued increase of radiative forcing beyond 2100. The RCPs served as inputs to more than 30 climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) to assess the changes they trigger in the climate system globally and regionally [I–2].

Relative to the 1850–1900 period, the increase in global surface temperature is likely to exceed 1.5°C by the end of this century for all but the RCP2.6 scenario. Relative to the IPCC AR5 reference period (1986–2005), global surface temperature is expected to rise between 0.3°C and 1.7°C (RCP2.6) at the low end of the scenario spectrum, and between 2.6°C and 4.8°C (RCP8.5) at the high end. The low end of the range is associated with limiting the global mean temperature increase to less than 2°C.

Figure I–1 shows the baseline (without climate policy) and the RCP2.6 mitigation pathways for all GHGs included in the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) and for energy and industry related CO_2 emissions alone. The chart indicates an enormous mitigation challenge: total GHG emissions will need to start decreasing at a fast rate in less than a decade, while energy and industry related CO_2 emissions will need to become negative beyond 2070. The latter will require a fast decarbonization of the energy system by adding carbon capture and storage (CCS) to a large fraction of fossil fuel and bioenergy use and by drastically increasing the contribution of nuclear energy and other low carbon sources to the global energy mix.

I–3. Global climate policy

The first step by the international community to address the climate change challenge was the UNFCCC, which was adopted at the Earth Summit in 1992 and entered into force in 1994. Article 2 specifies its ultimate objective: "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The third session of the Conference of the Parties (COP 3) adopted the Kyoto Protocol



Source: Data from Ref. [I–3].

FIG. I–1. Baseline and RCP2.6 emissions paths of all GHGs included in the Kyoto Protocol and of energy and industry related CO_2.

in 1997, in which industrialized countries (listed in annex I of the UNFCCC[2]) made commitments to reduce their collective GHG emissions during the period 2008–2012 by at least 5.2% below 1990 levels. Since the United States of America has not ratified the Kyoto Protocol, the actual reduction is expected to be only about 3.8% of the 1990 annex I emissions. This reduction is far outweighed by increases of emissions in non-annex I countries in the same period.

UNFCCC negotiations on the next steps started in 2005, but failed to produce an agreement on "long-term cooperative action" about mitigation, adaptation, finance and other issues by the 2009 deadline. COP 15 merely "took note" of the Copenhagen Accord, which recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius" and provided a framework for voluntary GHG emissions reductions by 2020 but involved no firm commitments [I–4]. In 2011, COP 17 established the formal legal amendment for a second commitment period under the Kyoto Protocol

[2] Annex I includes the member countries of the Organisation for Economic Co-operation and Development (drawing from the 1990 membership) as well as Belarus, Bulgaria, Croatia, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, the Russian Federation, Slovakia, Slovenia and Ukraine.

(without which the world would not have an international agreement after 31 December 2012 limiting GHG emissions) and launched the Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP) with a mandate “to develop a protocol, another legal instrument or an agreed outcome with legal force under the Convention applicable to all Parties” for adoption in 2015 and to enter into force in 2020.

Progress towards the new agreement has been very slow in the two years after COP 17. The ADP mandate involves a fundamental change from differentiating developed (annex I) and developing countries (non-annex I) concerning their legally binding mitigation commitments under the Kyoto Protocol by calling for an agreement applicable to all Parties. COP 19 in 2013 demonstrated large gaps between the positions of developed and developing countries about the preferred legal character of the agreement and about the differentiation of obligations. The COP 19 decision on ADP invited all Parties:

> “to initiate or intensify domestic preparations for their intended nationally determined contributions … towards achieving the objective of the Convention as set out in its Article 2 and to communicate them well in advance of the twenty-first session of the Conference of the Parties (by the first quarter of 2015 by those Parties ready to do so) in a manner that facilitates the clarity, transparency and understanding of the intended contributions, without prejudice to the legal nature of the contributions” [I–5].

As of early 2014, the ADP negotiations had been far from the level of detail at which Parties could consider approaches and mechanisms for implementing the new agreement. However, future outcomes of the discussions about frameworks for various approaches (new market, other market and non-market based mechanisms) and the related accounting rules may affect the choice of technologies under the post-2015 agreement. The applicability of the Bonn Agreements and the Marrakesh Accords — which practically excluded nuclear energy from two international flexibility mechanisms (the clean development mechanism and joint implementation) of the Kyoto Protocol — in implementing the new agreement remains uncertain at this point.

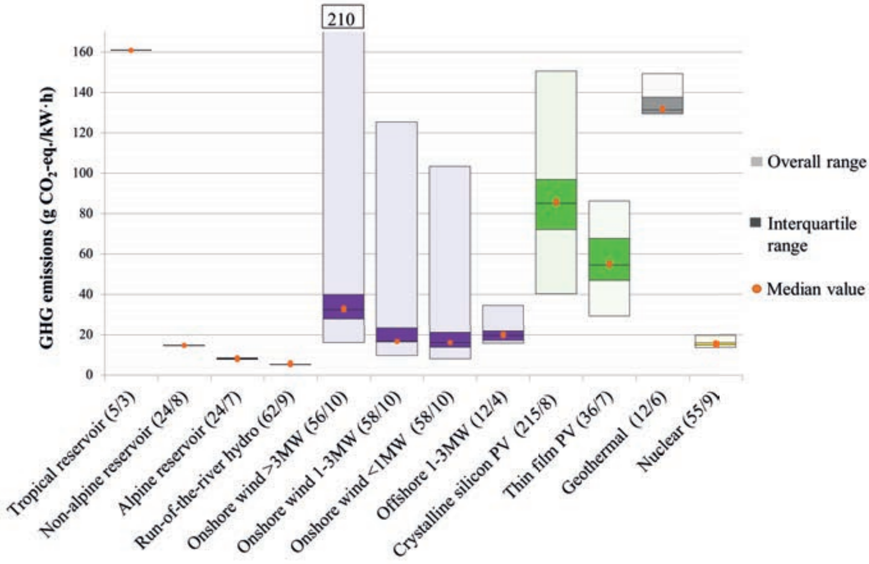
I–4. Nuclear energy in climate change mitigation

If the new global mitigation agreement embarks on sweeping GHG reduction pathways calculated by the scientific community, the importance of energy technologies emitting small amounts of GHGs per unit of energy service provided will increase. Because of this heightened importance, emissions need to be accurately identified and assessed. The appropriate method to quantify the total GHG emissions is life cycle analysis (LCA), accounting for all GHG emissions from the infrastructure (from construction to decommissioning of power plants and all equipment) and the associated fuel cycle (from mining to final waste disposal).

LCA is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a production system throughout its entire life cycle. The LCA of an electricity production system reflects its high complexity, encompassing many processes within its chosen system boundary that contribute to the final product. Because of its importance in the decision making process and the possible consequences of errors, consistency and credibility are of the utmost importance in LCA. Aiming to enhance quality, but without prescribing specific methodologies, relevant International Organization for Standardization (ISO) standards were introduced and currently present the norm for developing LCA studies, including GHG emissions of different electricity generation technologies.

Estimates of life cycle GHG emissions from electricity generation fuelled by lignite and hard coal vary in a wide range between 1000 and 1800 g carbon dioxide equivalent (CO_2-eq) per kWh around a median value of 1300 g CO_2-eq per kWh for lignite and 1150 g CO_2-eq per kWh for hard coal. Conventional gas fired power plants and modern combined cycle gas turbines emit considerably less GHGs: about 700 g CO_2-eq per kWh and 400 g CO_2-eq per kWh, respectively. Adding CO_2 CCS to fossil fired power plants, life cycle emissions would still remain high at about 200 g CO_2-eq per kWh for coal and about 150 g CO_2-eq per kWh for gas.

Figure I–2 presents GHG emissions for renewable energy sources and nuclear power. The median value of emissions from nuclear power (light water reactors) is estimated at 14.9 g CO_2-eq per kWh, with a range of 13.5–19.8 g CO_2-eq per kWh of generated electricity. The entire life cycle from uranium mining to waste disposal is taken into account in the underlying calculation. There are some regional variations around the global averages. The Japanese Central Research Institute of the Electric Power Industry (CRIEPI) calculated 19.5 g CO_2-eq per kWh for pressurized water reactors and 20.2 g CO_2-eq per kWh for boiling water reactors. Environmental Product Declarations (EPDs), based on British, Swedish and Swiss nuclear power LCA studies, have calculated considerably lower emissions at 4–6 g CO_2-eq per kWh [I–7].



Note: The numbers in parenthesis indicate the number of LCA calculations and the number of global regions in which those locations can be found. The interquartile range includes half of the calculations around the median of the whole range.
Source: Ecoinvent [I–6].

FIG. I–2. Life cycle GHG emissions from electricity generation: renewable technologies and nuclear power.

Median values for solar photovoltaic (PV), compared to nuclear power, range between four times (54.5 g CO_2-eq per kWh for thin film) and six times higher (85.2 g CO_2-eq per kWh for crystalline silicon). Wind power GHG emissions are comparable with those from nuclear power up to the class of 3 MW(e) wind turbines (see Fig. I–2). Above that, life cycle GHG emissions practically double, reflecting the higher use of energy and materials per unit of capacity for the construction of turbines with a capacity larger than 3 MW(e). Hydropower from alpine and non-alpine reservoirs, as well as run of river systems, also has comparable life cycle GHG emissions to nuclear power. Pumped storage systems show a very wide range (40.3–2004.6 g CO_2-eq per kWh) [I–6], depending on the carbon intensity of the electricity used to power the pumps that drive the water back to the reservoir for storage.

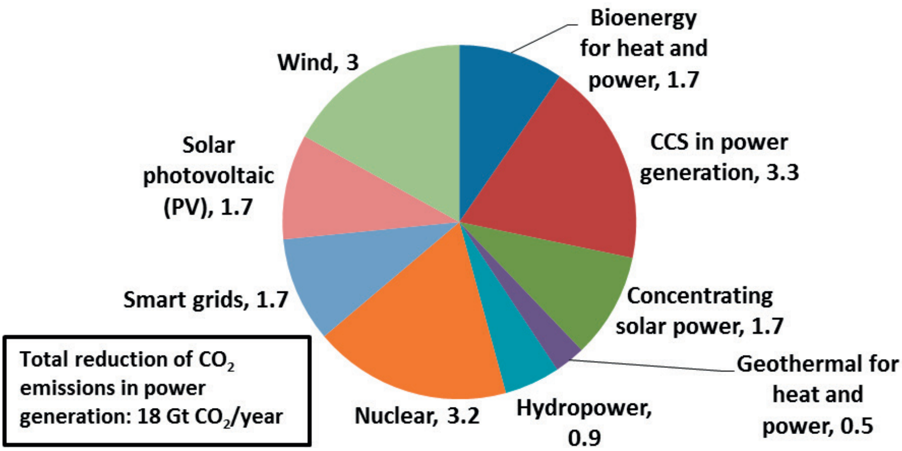
Life cycle GHG emissions from nuclear energy may well decrease in the future due to further improvements in:

(a) Uranium enrichment technologies, shifting from electricity intensive gaseous diffusion to centrifuge or laser technologies that require much less electricity;
(b) The increased share of electricity used for enrichment based on low carbon technologies;
(c) Improvements in fuel manufacturing, such as higher burnup, which reduces emissions per kilowatt hour associated with the fuel cycle;
(d) Extended nuclear power plant lifetime from 40 to 60 years, reducing emissions per kWh associated with construction and decommissioning.

The very low CO_2 and GHG emissions on a life cycle basis make nuclear power an important technology option in climate change mitigation strategies for many States. The figures demonstrate that nuclear power, together with hydropower and wind based electricity, remains one of the lowest emitters of GHGs in terms of gram CO_2-eq per unit of electricity generated. But what would be the share of nuclear energy in a mitigation portfolio based on its economic performance relative to other low carbon technologies?

The International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD) publishes a detailed energy technology assessment for the world every two years. Energy Technology Perspectives 2012 (ETP2012) presents an in-depth survey of energy technologies and prospects for their evolution up to 2050 [I–8]. The report presents a reference case called the 6°C Scenario (6DS), in which current policies and trends are extended into the future. Two policy scenarios — the 4°C Scenario (4DS) and the 2°C Scenario (2DS), reflecting the policy targets of limiting global mean temperature increase to 4°C and 2°C, respectively — are evaluated, with an emphasis on the 2DS. The 2DS is consistent with the Copenhagen Accord of the UNFCCC. The 2DS stipulates an ambitious pathway along which global, energy related CO_2 emissions peak before 2020 and decline to almost 50% of the 2009 level — that is, to around 17 Gt CO_2 — by 2050 [I–8].

According to the 2DS, the electricity sector will be substantially decarbonized by 2050. The contribution of various electricity generation technologies to this extraordinary development is presented in Fig. I–3. End use efficiency improvements, CCS and electricity production from nuclear represent the largest shares of the low cost mitigation opportunities within the power sector. CCS accounts for 3.3 Gt CO_2/year (18%) and nuclear about 3.2 Gt CO_2/year (17%) of the power sector's CO_2 reductions.



Source: IEA [I–8].

FIG. I–3. The contribution of mitigation options to CO_2 emissions reduction in the power sector in 2050.

The driving force behind CO_2 mitigation in the electricity sector is renewables, which is projected to grow to a 57% share of generation by 2050 in the 2DS. Nuclear energy is also a significant contributor to generation in the electricity sector in the 2DS with a 19% share by 2050, and CCS is close behind at 14%. The ETP2012 also presents a high nuclear case combined with a 2DS, and in this scenario, nuclear reaches a 34% share by 2050, largely by crowding out some renewables and coal with CCS. According to the ETP2012, this high nuclear scenario "reflects a world with larger public acceptance of nuclear power" and assumes average construction rates of almost double the 27 GW/year of the 2DS to 50 GW/year [I–8]. This variant also assumes a larger nuclear fuel supply through recycling spent fuel and unconventional uranium sources.

I–5. Conclusions

Recent scientific evidence confirms that unconstrained emissions of GHGs from human activities would lead to considerable changes in the Earth's climate system with distressing impacts on ecological and socioeconomic systems. Global energy demand will keep increasing. However, in order to keep the increase in global mean temperature below 2°C relative to pre-industrial levels, GHG emissions should stop increasing within the next decade or so and then should fall substantially below the 2000 emission levels by the middle of the century. International negotiations to achieve the required emissions reductions have achieved modest results so far. Accomplishing the ADP mandate under the

UNFCCC to establish a legally binding global agreement for reducing GHG emissions beyond 2020 is a fundamental element of international environmental policy.

Nuclear power belongs to the set of energy sources and technologies available today that could help meet the climate–energy challenge. GHG emissions from nuclear power plants are negligible and nuclear power, together with hydropower and wind based electricity, is among the lowest CO_2 emitters when emissions through the entire life cycle are considered. In a cost minimizing mitigation portfolio, nuclear energy could account for about 17% of the total CO_2 emissions reduction in power generation in 2050. If the use of any low carbon technology were restricted or if it were excluded from the mitigation mix, the costs would increase and the environmental effectiveness of mitigation policies would be reduced. Therefore, cost efficiency, environmental effectiveness and timely reduction measures are important factors to consider in the 2015 UNFCCC agreement on mitigation commitments and implementation mechanisms.

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Annex II

THE ROLE OF NUCLEAR KNOWLEDGE MANAGEMENT

II–1. Introduction

The IAEA has been a focal point for nuclear knowledge and information since its establishment in 1957. Nuclear knowledge management (NKM) came to the forefront formally in the twenty-first century, when several resolutions adopted at the IAEA's General Conference, from 2002 onwards, included NKM as a high priority for Member States [II–1].

This annex summarizes how NKM assists Member States in enhancing and supporting national nuclear policy and strategy and in ensuring safe and sustainable operation of nuclear facilities.

Nuclear knowledge is complex. Figure II–1 illustrates in three dimensions the aspects that need to be managed. The first dimension concerns the primary knowledge domains: people, processes and nuclear technology. People need to have the necessary combination of appropriate skills, experience, attitude and motivation. Processes methods and practices need to be controlled in an orderly and consistent way. Technology must be well understood and maintained. The second dimension concerns the nuclear life cycle from R&D through design and licensing, construction, commissioning, operations, maintenance, refurbishment

FIG. II–1. NKM complexity and scope.

and finally decommissioning. The third dimension recognizes the different nature of individual expertise, organizational competency and national capacity.

II–2. Role of NKM in nuclear organizations

It has become increasingly clear to Member States that creating, sharing and transferring knowledge is critical for the safe and efficient management of any nuclear activity. Many Member States now have knowledge management programmes in place and are gaining a better understanding of the unique characteristics of nuclear knowledge to fulfil the missions and visions of each organization.

II–2.1. Research and development

Innovation requires a holistic approach to problem solving and the ability to link separate concepts together to produce a new result. The process can be carried out by individuals, but better results are usually achieved by teamwork and group collaboration. Social interaction is therefore a key success factor for innovation. The resulting outcome is often an intangible knowledge asset that should be managed appropriately.

As R&D projects grow, international strategic alliances are increasingly required. Such collaboration and partnership between R&D institutes, government, universities and industry need a flexible approach, and this process can be facilitated through various knowledge management tools and techniques.

Advanced nuclear education and the supply of qualified graduates are both important for nuclear R&D organizations to meet the ongoing demand for technical specialists. Successful delivery of nuclear education and training programmes now typically includes the transfer of knowledge through e-learning or online classroom environments as well as the traditional in-class lecture approach [II–2].

II–2.2. Nuclear power plants

The importance of NKM activities at nuclear power plants has been clear for the last decade. There are numerous examples of NKM good practices collected by the IAEA from States such as Canada, France, Germany, Japan, the Russian Federation, Ukraine, the United Kingdom and the United States of America, which are using NKM to solve new and existing challenges.

Long term operation requires the transfer of the most critical knowledge from one generation to another, and new-builds in States embarking on a nuclear power programme require new competencies and approaches to manage knowledge from the very beginning of the project. Today, many nuclear power plants have embedded NKM in their integrated management systems to ensure that knowledge flows effectively through and within the organization.

NKM plays an essential role in not only performance optimization, but also in supporting safety culture, learning, trust, collaboration and knowledge sharing.

II–2.3. Waste management facilities

Most nuclear related activities will produce associated radioactive waste. Waste management demands a commitment over several generations to protect living organisms and the environment. Information about the radioactive waste and its management or disposal should be collected and stored, regardless of the method of disposal that is eventually selected. Decisions on waste management approaches should be driven by technical knowledge based on experience accumulated over many years.

II–2.4. Regulators

Regulatory bodies develop safety regulations and authorization processes, review and assess the safety and design documentation provided by the operating organization, and inspect the facility, vendors and manufacturers of safety related components. They must maintain the highest levels of competence to understand the design basis of nuclear technology systems.

II–3. Knowledge management survey of nuclear power plants

In 2013, the IAEA published the results of an empirical survey that investigated the relationship between knowledge management practices in nuclear power plants and their impact on organizational effectiveness [II–3]. A total of 124 ‘site organizations’ participated in the survey, representing a response rate of approximately 60%. The findings show that nuclear power plant organizations with higher levels of support for knowledge management practices have higher levels of organizational effectiveness, measured against a range of performance measures that include safety, economic, operations and maintenance indicators.

The findings clearly show that the mechanism by which knowledge management practices and information technology influence organizational effectiveness is not direct. It is primarily through their positive effect on organizational culture and on improving the quality of knowledge processes in the organization. These findings are helping nuclear power plant managers to better understand the mechanism by which knowledge management practices improve organizational effectiveness.

II–4. Role of NKM in nuclear education

Education is a key component of knowledge management. Any national nuclear energy programme depends on the successful development of a competent workforce, through a sustainable academic or university education and industry training. In the broad range of specialists, the nuclear engineer is a vital component of any nuclear workforce. The IAEA is preparing a technical report on nuclear engineering education and curricula development focusing mainly on nuclear power [II–4].

Nuclear engineering education programmes can also be supported by IAEA services such as assistance visits, expert missions, provision of documentation and educational tools, coordination of educational networks and train the trainers workshops for educational providers.

Education significantly benefits from educational networks, which allow for sharing of resources, experiences and best practices [II–5]. A number of national and regional networks and consortia are playing important roles in sharing curricula, programmes and opportunities for students. In Canada, for example, the University Network of Excellence in Nuclear Engineering has a strong link with the industry. In the Russian Federation, the National Research Nuclear University, centred on the Moscow Engineering Physics Institute, brings together 23 campuses across the country. In France, the International Institute of Nuclear Energy was created under the auspices of the French Council for Education and Training in Nuclear Energy. In the United Kingdom, the Nuclear Technology Education Consortium provides a one stop shop for a range of postgraduate programmes. In Latin America, the Mexican Network for Education, Training and Nuclear Research and the Argentine Nuclear Education Network were created to facilitate cooperation and to promote the preservation of knowledge. In Asia, the Japan Nuclear Human Resource Development Network was created to coordinate and concentrate efforts. In Europe, the European Nuclear Education Network links universities from a number of countries and helps to promote quality uniform curricula in nuclear education. They have created a European Master of Science in Nuclear Engineering.

The IAEA has also founded similar initiatives in Asia, Latin America and Africa: the Asian Network for Education in Nuclear Technology (ANENT); the Latin America Network for Education in Nuclear Technology (LANENT); and the AFRA Network for Education in Nuclear Science and Technology (AFRA-NEST). There is a movement to form a new regional education network led by the Russian Federation and other members of the Commonwealth of Independent States.

II–5. Application of NKM and initiatives for nuclear education and training in Member States

Many Member States have applied NKM in their initiatives and activities and facilitated various programmes on nuclear education and training.

In the Russian Federation, building on positive results in developing an infrastructure for utilizing corporate knowledge to improve safety culture and organizational performance, the State Atomic Energy Corporation “Rosatom” established a knowledge management programme to promote knowledge transfer and innovation. The programme consists of three parts: management of intellectual property rights; knowledge preservation through digitalization and content management; and management of scientific and technical communities with a special focus on the transfer of poorly formalized and non-formalized knowledge. Rosatom, in cooperation with the IAEA, held the International Conference on Knowledge Management and Innovation: Lessons Learned from Technology Leaders, which attracted more than 400 specialists and 120 companies to Moscow in December 2012.

In Europe, the Joint Research Centre of the European Commission launched the European Human Resources Observatory for the Nuclear Energy Sector (EHRO-N) to monitor the needs of human resources and expertise for the different stakeholders in nuclear energy and nuclear safety. EHRO-N is also preparing job taxonomy, applying the principles of the European Credit System for Vocational Education and Training to facilitate the validation, recognition and accumulation of work related skills and knowledge acquired during a stay in another country or in different situations.

The World Nuclear University (WNU) is a global partnership committed to enhancing international education and leadership in the peaceful application of nuclear science and technology. WNU programmes, such as the Summer Institute, have focused on building nuclear leadership and providing orientation on the main issues that affect the current global nuclear industry. Over 3500 nuclear professionals and students from over 60 countries have participated in such programmes.

The Abdus Salam International Centre for Theoretical Physics, which operates under a tripartite agreement between the Italian government, the IAEA, and the United Nations Educational, Scientific and Cultural Organization, has been a driving force behind global efforts to advance scientific expertise in developing countries. It organizes more than 60 international conferences, workshops, and numerous seminars and colloquiums including the IAEA’s

Nuclear Knowledge Management School and Nuclear Energy Management School for young nuclear professionals.

International conferences in this area are regularly conducted by different organizers all over the world. These include the Conference on Nuclear Training and Education of the American Nuclear Society, the NESTet Nuclear Education and Training conferences of the European Nuclear Society, and the International Conference on Nuclear Human Resource Development for the Asia and Pacific Region, organized by the Japan Atomic Energy Agency as part of the activities of the Japan Nuclear Human Resource Development Network.

II–6. Role of design knowledge management over the life cycle

Nuclear technology is complex. Plants are designed to achieve a high level of safety performance under normal conditions, during anticipated operational occurrences and during design basis accidents. The IAEA focuses its attention on the importance of the management and adequate understanding of design basis information from the beginning of the life cycle. For example, key knowledge about design assumptions or constraints, design or operating limits and conditions, in-service testing and inspection, maintenance history, operating performance and component life should be documented. They are important aspects of design knowledge that have to be preserved and managed. They are needed for safe operation, maintenance and any design changes. This knowledge is created, captured, used, modified, transferred and maintained by various stakeholders and at various times over the life cycles of the technology and the facility. Stakeholders producing and using this knowledge may include R&D organizations, vendors, regulators, owner and operators, technical service organizations, owners' groups and even suppliers (see Fig. II–2).

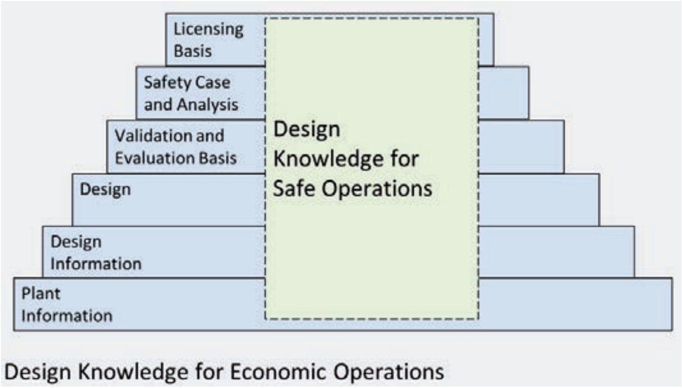

FIG. II–2. Design basis information exists in many forms.

It is important to establish effective knowledge transfer mechanisms from vendor to utility during the new-build process. The IAEA is helping newcomer countries to understand the complexity of the challenge, in particular with respect to design knowledge and information. The documentation and the technical competencies needed to verify and validate the design basis are complex and very knowledge dependent. The volume of design information on the various systems and components is extremely large and must be subject to strict revision control, formal review and approval processes, as well as configuration management.

II–7. Communities of practice

Communities of practice (CoPs) are often at the heart of an organization's knowledge management system. They support the development and maintenance of organizational and personal competency through activities such as incorporating expertise into improved practices, recognizing and introducing new external knowledge, codifying and validating knowledge, as well as sharing knowledge by connecting experts, knowledge workers and knowledge seekers across organizational and national boundaries.

CoPs are networks of people who work on similar processes or in similar technical disciplines, and who come together to develop and share their knowledge for the benefit of themselves, other members of the community and their organizations. CoPs can be created and sustained formally or informally and organizations are now finding it beneficial to proactively enable CoPs. The lifespan of a community typically exceeds that of projects and organizational structures, making it an ideal mechanism for preserving nuclear expertise within a dynamic industry. CoPs interact with both face to face activities and information and communications technologies (ICT), making it possible for geographically dispersed networks to operate efficiently. An example of such a CoP is the Nuclear Energy Institute's Equipment Reliability Working Group.

The IAEA actively cultivates CoPs and promotes their benefits by encouraging industry leaders to support them, publishing guidance on improving their performance, providing an ICT infrastructure for international cooperation, maintaining a directory of CoPs that enables connections between CoPs and individuals seeking to share expertise, encouraging existing CoPs to work with possible problems and promoting the creation of an international community of practice on NKM.

II–8. Importance of knowledge transfer to developing countries

II–8.1. Capacity assessment and planning

Many developing countries have pockets of achievement in nuclear technology applications. However, the lack of effective science, technology and innovation policy, which provide guidelines on technology transfer, including nuclear education, training and local technology development, continues to be a stumbling block for converting such achievement into sustainable national development.

Hence, there is a need to develop an integrated nuclear education system capability assessment and planning (CAP) framework, focused at the national level. This should take into consideration the full scope of government priority areas, external factors that affect the implementation, and the transfer and use of peaceful non-power applications of nuclear science and technology.

The IAEA is developing a generic, holistic model for the CAP framework through a set of pilot projects with States in the African region that can be applied to other States as appropriate.

II–8.2. Preservation of reactor technology knowledge

A taxonomy is a hierarchical system in which information or knowledge is categorized, allowing an understanding of how that body of knowledge can be broken down into parts, and how its various parts relate to one another. It enables users to find the targeted data easily and systematically.

Fast reactor technology continues to be developed in some Member States. The IAEA has been developing the taxonomy for the Fast Reactor Knowledge Organizational System (FR-KOS) and the VVER Knowledge Organizational System (VVER-KOS). There is a potential risk of knowledge loss in these areas, as many specialists have already retired, or are retiring, and projects last several decades.

In light of the Fukushima Daiichi nuclear accident, it is recognized that valuable data and lessons learned should be effectively shared to prevent similar accidents from happening again. To this end, the IAEA is creating a database to preserve knowledge about major nuclear accidents.

II–9. Conclusion

Nuclear knowledge and its effective management are critical drivers of both performance and safety for all nuclear organizations, from nuclear power plants through to regulators and educational establishments. Nuclear facilities operate over very long timescales, during which operational conditions and technologies change. Knowledgeable decision making is vital throughout this nuclear life cycle, as anything less than a full understanding of the potential consequences of decisions and actions may compromise nuclear safety. Effective knowledge management informs and supports business and decision processes throughout the whole nuclear sector by ensuring that the right knowledge is available for decision makers and operators when required.

Organizations involved in the nuclear sector have demonstrated that they appreciate the significance and benefits of having in place robust and comprehensive knowledge management policy and procedures. During 2013, Member States actively contributed towards enhancing best practices in knowledge management. The IAEA has continued to assist Member States in their endeavours by developing guidance on, and methodologies for, planning, designing and implementing NKM programmes. This assistance includes the fostering and preservation of nuclear education capabilities.

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