NUCLEAR TECHNOLOGY REVIEW

2013

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2013

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EXECUTIVE SUMMARY

Nuclear power's global generating capacity grew to 372.1 GW(e) in 2012 with 437 reactors in operation at the end of the year. Three new reactors were connected to the grid, and two reactors that had been in 'long term shutdown' were restarted. Only three reactors were permanently shut down in 2012 as compared with thirteen in 2011. Sixty-seven new reactors were under construction at the end of the year, a figure which remains quite high. Significant growth in the use of nuclear energy worldwide is anticipated — between 23% and 100% by 2030 — although IAEA projections for 2030 are 1–9% lower than projections made in 2011. Most of the growth is expected in countries that already have nuclear power plants in operation, particularly in the Far East where projected growth is strongest.

Although some countries have delayed decisions to start nuclear power programmes, others continued with their plans to introduce nuclear energy. In July 2012, the United Arab Emirates (UAE) became the first country in 27 years to start the construction of a first nuclear power plant. In addition to the UAE, several other countries, including Belarus and Turkey, have made progress towards their first nuclear power plant in 2012.

In the 2011 edition of the 'Red Book', Uranium 2011: Resources, Production and Demand, issued jointly by the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD/NEA) and the IAEA, estimates of identified conventional uranium resources recoverable at a cost of less than \$130/kg U decreased slightly compared to the previous edition, as uranium production worldwide rose significantly, largely as a result of increased production in Kazakhstan. Additional resources were reported throughout 2011 for many uranium deposits in Africa. Uranium spot prices, which at the end of 2011 were at \$135/kg U, dropped by the second half of 2012 to around \$110/kg U. At the end of 2012, uranium spot prices rose to around \$115/Kg U. However, long term prices for uranium remained steady at around \$158/kg U.

The Georges Besse Gas Diffusion Plant in France, which closed in June 2012, has been replaced by the Georges Besse Uranium Enrichment Plant II. In September 2012, the United States Nuclear Regulatory Commission issued the first ever construction and operation licence for a full scale laser enrichment facility to Global Laser Enrichment, a subsidiary of GE Hitachi Nuclear Energy.

In July 2012, the Korea Atomic Energy Research Institute completed construction of the Pyroprocess Integrated Inactive Demonstration Facility for pyroprocessing spent oxide fuel. Startup tests began in August.

In the area of radioactive waste management, in Canada, the development of three geological disposal facilities is being considered: the Bruce site facility for LLW and ILW from Ontario Power Generation, the Chalk River Laboratories site for LLW and ILW, and a third site, as yet undefined, for Canada's Used Nuclear Fuel Repository and Centre of Expertise. In Spain, Villar de Cañas was officially selected as the site for the central storage of Spain's used nuclear fuel in December. Also in December, Posiva in Finland submitted a repository construction licence application to the Finnish Government for its spent fuel disposal facility at Olkiluoto, with final disposal expected to begin in 2020.

Construction began in 2012 on one new research reactor, a 5 MW multipurpose research reactor in Jordan. As of January 2013, there were 247 research reactors in operation. The IAEA continued to support global efforts to minimize the use of highly enriched uranium (HEU) fuel in research reactors. In September 2012, the Maria research reactor in Poland was converted from HEU to low enriched uranium (LEU) fuel. The TRIGA Mark III research reactor in Mexico was converted from HEU to LEU fuel, and its final HEU fuel was shipped back to the United States of America in March 2012. In December 2012, the final removal of all HEU from Austria took place following the complete conversion of the Vienna TRIGA reactor to LEU fuel. The efforts in Austria and Mexico marked the removal of all TRIGA HEU fuel from civilian nuclear applications worldwide. Under the Russian Research Reactor Fuel Return programme, in 2012 the IAEA assisted in the repatriation of nearly 110 kg of fresh HEU fuel from the Kharkov Institute of Physics and Technology, Ukraine, approximately 20 kg of HEU spent fuel from the Institute for Nuclear Research in Kiev, nearly 100 kg of HEU spent fuel from Uzbekistan and Poland and 27 kg of fresh HEU fuel from Poland.

The nuclear applications addressed in this Nuclear Technology Review reflect three areas of topical and significant interest: the use of nuclear technologies to improve food safety and security, new developments in combating cancer and nuclear technologies to address the impacts of climate change.

Food safety and security is enhanced through food irradiation, which involves exposing food to ionizing radiation under controlled conditions. Irradiation facilities commonly use cobalt-60 or caesium-137 radioisotopes to provide gamma rays. However, it is proving difficult to increase the application of food irradiation using these radioisotopes because of the complexity of procuring, shipping and receiving radioisotope sources. As a result, there is growing interest in e-beam (electron beam) and X ray technology, which use electricity to produce ionizing radiation. These technologies offer the potential to significantly expand the application of food irradiation to enhance food safety and help increase the global food supply through the reduction of food losses and waste.

Food safety is a serious concern following a release of radioactivity from a nuclear accident. Nuclear techniques are used in harmonized field and laboratory practices being developed so that agricultural authorities can effectively and consistently assess food safety as soon as possible after a nuclear event. Lessons learned from accidents have shown that the reporting and management of food and agriculture data need to be improved, especially where several countries are affected and a coordinated approach is necessary.

Radiotherapy, which aims to deliver an accurate dose of radiation to a tumour with minimal damage to normal surrounding tissues, is an effective cancer treatment. Recent advances in photon radiotherapy offer potentially substantial advantages over conventional radiotherapy, including improved dose distribution, reduced toxicity, quick treatment delivery and more precise local control, all leading to increased chances of survival. The past two decades have seen an increased interest in and development of particle therapy, in particular proton beam therapy and carbon-ion beam therapy. A further development is in the use of three dimensional brachytherapy, where the radiotherapy is carried out by placing radioactive sources adjacent to or in tumours or body cavities. The use of these advanced technologies involves additional, significant costs, which must be weighed against the potential benefits of these technologies over traditional methods.

The manipulation of matter at the atomic and molecular level to devise new materials, devices and structures is called nanotechnology. One interesting development is in the area of medicine. Particular properties of certain nanostructures could help to fight cancer using unprecedented approaches. This has spawned the new field of nanomedicine, defined as the medical application of nanotechnology. In targeting cancer cells, customized nanoscale systems can serve as drug delivery vehicles capable of delivering large doses of radionuclides into malignant cells while sparing normal tissues and thus greatly reducing the side effects that usually accompany many current cancer therapies.

Nuclear techniques play an important role in understanding climate change, predicting its future course and adapting to its impacts. In the marine environment, the impacts of climate change such as ocean acidification are affecting fisheries, coastal aquaculture, coral reefs and other coastal resources. Nuclear technologies provide answers to some of the basic scientific questions about the interaction between environmental conditions in the ocean and marine ecosystems and organisms. The use of both radionuclides and stable isotopes has helped to provide a better understanding of the occurrence of the El Niño Southern Oscillation phenomenon over a period going back several millennia. Nuclear techniques are also being used to study the impacts of ocean acidification on marine ecosystems and biodiversity.

A. POWER APPLICATIONS

A.1. Nuclear power today

As of 31 December 2012, there were 437 nuclear power reactors in operation worldwide, with a total capacity of 372.1 GW(e)[1] (see Table A-1). This represents a slight increase of some 3.3 GW(e) in total capacity, compared to the 2011 figures. There were three new grid connections: Ningde 1 (1000 MW(e)) in China and Shin-Wolsong-1 (960 MW(e)) and Shin-Kori-2 (960 MW(e)) in the Republic of Korea. In addition, two laid-up units, Bruce 1 and 2 (772 MW(e) each), were reconnected in Canada.

The impact of the accident at the Fukushima Daiichi nuclear power plant continued to be felt in 2012 in the relatively low overall number of construction starts on new reactors. There were seven construction starts in 2012: Fuqing 4, Shidao Bay 1, Tianwan 3 and Yangjiang 4 in China, Shin-Ulchin-1 in the Republic of Korea, BALTIC 1 in the Russian Federation, and Barakah 1 in the United Arab Emirates (Fig. A-1). Although higher than the 2011 figure, this is significantly fewer than in 2010, when the steady increase which began in 2003 reached its peak with 16 construction starts.

FIG. A-1. Construction at Barakah 1 in the UAE (Photograph courtesy of ENEC).

[1] 1 GW(e) 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 2012)[a]

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2012		Total operating experience up to 2012	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW/h	% of total	Years	Months
Argentina	2	935	1	692	5.9	4.7	68	7
Armenia	1	375			2.1	26.6	38	4
Belgium	7	5 927			38.5	51.0	254	7
Brazil	2	1 884	1	1 245	15.2	3.1	43	3
Bulgaria	2	1 906			14.9	31.6	153	3
Canada	19	13 500			89.1	15.3	634	5
China	17	12 860	29	28 844	92.7	2.0	141	7
Czech Republic	6	3 804			28.6	35.3	128	10
Finland	4	2 752	1	1 600	22.1	32.6	135	4
France	58	63 130	1	1 600	407.4	74.8	1 874	4

For footnotes see p. 9.

TABLE A-1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2012)[a] (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2012		Total operating experience up to 2012	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW/h	% of total	Years	Months
Germany	9	12 068			94.1	16.1	790	2
Hungary	4	1 889			14.8	45.9	110	2
India	20	4 391	7	4 824	29.7	3.6	377	3
Iran, Islamic Republic of	1	915			1.3	0.6	1	4
Japan	50	44 215	2	2 650	17.2	2.1	1 596	4
Korea, Republic of	23	20 739	4	4 980	143.5	30.4	404	1
Mexico	2	1 530			8.4	4.7	41	11
Netherlands	1	482			3.7	4.4	68	0
Pakistan	3	725	2	630	5.3	5.3	55	8
Romania	2	1 300			10.6	19.4	21	11

For footnotes see p. 9.

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	No. of units	Total MW(e)	No. of units	Total MW(e)	TW/h	% of total	Years	Months
Russian Federation	33	23 643	11	9 297	166.3	17.8	1 091	4
Slovakia	4	1 816	2	880	14.4	53.8	144	7
Slovenia	1	688			5.2	36.0	31	3
South Africa	2	1 860			12.4	5.1	56	3
Spain	8	7 560			58.7	20.5	293	6
Sweden	10	9 395			61.5	38.1	402	6
Switzerland	5	3 278			24.4	35.9	189	11
Ukraine	15	13 107	2	1 900	84.9	46.2	413	6
United Arab Emirates			1	1 345				
United Kingdom	16	9 231			64.0	18.1	1 511	8

For footnotes see p. 9.

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Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2012		Total operating experience up to 2012	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW/h	% of total	Years	Months
United States of America	104	102 136	1	1 165	770.7	19.0	3 834	8
Total[b, c]	437	372 069	67	64 252	2 346.2		15 246	9

[a] Data are from the IAEA's Power Reactor Information System (PRIS) (http://www.iaea.org/pris)
[b] Note: The total figures include the following data from Taiwan, China:
— 6 units, 5028 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 40.4 TW·h of nuclear electricity generation, representing 19.0% of the total electricity generated.
[c] The total operating experience also includes shutdown plants in Italy (81 years), Kazakhstan (25 years, 10 months), Lithuania (43 years, 6 months) and Taiwan, China (188 years, 1 month).

On the other hand, in 2012, only three reactors were officially declared permanently shut down: Gentilly-2 in Canada and Oldbury-A1 and Wylfa 2 in the United Kingdom. They had been operating for 30 years, 45 years and 41 years, respectively. This is significantly fewer than the 13 shutdowns in 2011.

As of 31 December 2012, 67 reactors were under construction (e.g. Fig. A-2), a figure which remains quite high. As in previous years, expansion as well as near and long term growth prospects remain centred in Asia (see Table A-1), particularly in China. Of the total number of reactors under construction, no fewer than 47 are in Asia, as are 38 of the last 48 new reactors to have been connected to the grid.

FIG. A-2. Construction at Shin-Kori-3 in the Republic of Korea.

In the USA, for the first time in the past 30 years, licences were issued in 2012 to build and operate four AP1000 units at Vogtle and V.C. Summer Nuclear Stations.

There is continuing interest around the world in the long term operation of existing plants. The IAEA organized the Third International Conference on Nuclear Power Plant Life Management (PLIM) in Salt Lake City, Utah, USA, in May 2012, with the sponsorship of the US Department of Energy and the Nuclear Regulatory Commission (NRC). Over 350 participants representing 38 Member States and 3 international organizations attended the conference and discussed the impact of the Fukushima Daiichi accident on PLIM and long term operation.

In 2012, the trend of power uprates and of renewed or extended licences for operating reactors continued in many countries. In France, the French Nuclear

Safety Authority granted a ten year renewal of the operating licence for unit 2 at the Bugey nuclear power plant (NPP) beyond 30 years, the third French unit to receive such an authorization. In the UK, the Nuclear Decommissioning Authority was given permission to continue operating Wylfa-1 until September 2014 by transferring partially used fuel from unit 2. In the USA, the NRC renewed the operating licences for the units at Pilgrim and Columbia NPPs for an additional 20 years, bringing the total number of approved licence renewals in the country to 73 since 2000. In addition, there were 13 licence renewal applications under review. Furthermore, 6 uprate applications were approved by the NRC in 2012 and 16 power uprate applications were also under review.

Two reactors were at least temporarily shut down due to impacts of reactor aging. During a scheduled outage at Doel-3 in Belgium, ultrasonic in-service inspections checked for underclad cracking in the reactor pressure vessel. The inspections found no underclad defects but did find a large number of nearly laminar indications mainly in the lower and upper core shells. A similar inspection in September at Tihange-2 showed similar indications but to a lesser extent. As a consequence, Doel-3 and Tihange-2 remained in cold shutdown at the end of the year while the utility performed an engineering evaluation to determine if either can be safely returned to service.

In Belgium, in view of the unusually large number of indications found in Doel-3 and Tihange-2, the Federal Agency for Nuclear Control has assembled a group of international experts in the fields of reactor vessel technology, non-destructive testing, fracture mechanics, ASME XI code evaluation, deterministic safety assessment and probabilistic safety assessment.

In Japan, Ohi-3 and Ohi-4 were restarted in July 2012, becoming the first two units to return to service following the March 2011 Fukushima Daiichi accident. The future of nuclear power in Japan was debated throughout the year. After the Liberal Democratic Party won the national election in December, the new Prime Minister, Shinzo Abe, announced that the government would review the national energy mix in the coming years and revisit the nuclear energy policy that had been announced by the previous government.

Nuclear power remains an important option to increase electricity production for countries with growing energy requirements, and important steps were taken in 2012 by countries planning to introduce nuclear power. On 18 July 2012, the United Arab Emirates became the first country in 27 years to start the construction of a first nuclear power plant, when the Emirates Nuclear Energy Corporation (ENEC) poured the first concrete after receiving a construction licence from the Federal Authority for Nuclear Regulation. The Barakah 1 unit is scheduled to be in operation by 2017 and three additional units are planned for 2020.

Several other countries took practical steps in 2012 towards constructing their first nuclear power plant. In June 2012, Belarus hosted an Integrated Nuclear Infrastructure Review (INIR) mission, which concluded that Belarus is on its way to being well prepared for a nuclear power programme. The country signed a contract in July 2012 with the Russian Federation's Atomstroyexport to do site work and build two water cooled water moderated power reactor (WWER) units. Turkey is also moving forward with its programme, having signed a contract in 2010 to build four WWER 1200 units at the Akkuyu site. Turkey also announced at the General Conference in 2012 that it is planning to build a second NPP at the Sinop site, and is negotiating with vendors. Additional countries have also confirmed their intention to proceed with developing a national nuclear power programme; these have continued building infrastructure and are considering possible contractual arrangements. A few other Member States are actively preparing for a nuclear power programme, but have not taken a final decision on whether to go ahead with its implementation.

In addition to Belarus, two other INIR missions were conducted in 2012, one to Jordan and one to Vietnam. The INIR mission to Jordan, which was conducted in January, was a follow-up mission to review the country's action plan, developed in response to the recommendations from the first INIR mission conducted in August 2009. It was noted that progress had been made in Jordan since 2009, especially in activities related to the nuclear power plant project. The INIR mission to Vietnam was successfully conducted in December.

The IAEA's INIR missions are one part of a holistic package to support sustainable energy development. In addition to INIR missions, the IAEA helps interested Member States increase their capabilities in analysing and planning their national energy systems and, for those with operating or planned nuclear power programmes, their capabilities for long term strategic planning of their nuclear energy systems. In 2012, the IAEA's tools for analysing and planning national energy systems were used in more than 125 Member States. Over 650 energy analysts and planners from 69 countries were trained to use these tools. For the long term strategic planning of nuclear energy systems, the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) provides a methodology, other tools, training and assistance in conducting Nuclear Energy System Assessments (NESAs). In 2011–2012, NESAs were initiated or ongoing in Belarus, Indonesia, Kazakhstan and Ukraine.

The IAEA leverages its training assistance through cooperation with national centres around the world. In July, it signed a practical arrangement with the Korea Electric Power Corporation International Nuclear Graduate School (KINGS). KINGS's mission is to facilitate access to the Korean education and training system on peaceful uses of nuclear energy for foreign students and employees. The practical arrangement lays the foundation for cooperation on international student recruitment, curriculum and seminar and outreach programme operation. In October 2011, the IAEA signed a practical arrangement with the China Atomic Energy Authority on cooperation in the field of safe nuclear power plant construction. The arrangement provides for stronger collaboration between the IAEA and China's International Construction Training Centre to ensure the safe construction of new nuclear power plants.

Of the commercial reactors in operation, approximately 82% are light water moderated and cooled reactors; 11% are heavy water moderated heavy water cooled reactors; 3% are gas cooled reactors; and 3% are water cooled and graphite moderated reactors (Fig. A-3). Two reactors are liquid metal moderated and cooled.

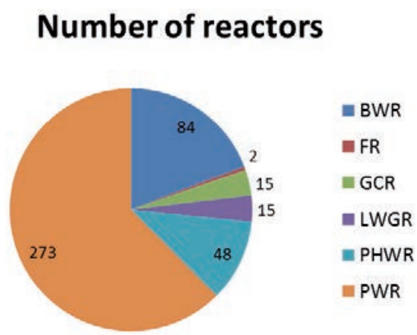

FIG. A-3. Current distribution of reactor types. (BWR: boiling water reactor; FR: fast reactor; GCR: gas cooled reactor; LWGR: light water cooled, graphite moderated reactor; PHWR: pressurized heavy water reactor; PWR: pressurized water reactor).

Although the nuclear industry has historically pursued economies of scale, there is growing interest in small and medium sized reactors (SMRs), partly because they allow smaller, more flexible and incremental investment over time. 'Small' means fewer than 300 MW(e). 'Medium sized' means between 300 MW(e) and 700 MW(e). Approximately 45 innovative SMR concepts are at some stage of research and development. Some of these are described in the following paragraphs.

Argentina is developing the CAREM-25 reactor, a small, integral type pressurized light water reactor (LWR) design with all primary components located inside the reactor vessel and an electrical output of 150–300 MW(e). Site excavation started in September 2011 for a 27 MW(e) CAREM prototype plant.

The China National Nuclear Corporation (CNNC) is developing the ACP100, a small integrated modular advanced pressurized water reactor of 100 MW(e) which can also be used for heat and seawater desalination. It is also developing the ACP600, a 600 MW(e) two loop advanced pressurized water reactor which is suitable for electricity grids with smaller capacity.

In France, the company DCNS is developing Flexblue, a small and transportable modular design 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, an infinite and permanently available heat sink.

In Japan, a 350 MW(e) LWR with an integral primary system called the Integral Modular Reactor (IMR) has been developed. Validation testing, research and development for components and design methods and basic design development are required before licensing. Japan has also been developing the 4S, a liquid sodium cooled fast reactor without on-site refuelling. The design offers two alternative output levels: 30 MW(th) and 135 MW(th).

The Republic of Korea's system integrated modular advanced reactor (SMART) design has a thermal capacity of 330 MW(th) and is intended for seawater desalination. Standard design approval was granted by the national Nuclear Safety Commission in 2012.

The Russian Federation is building two 35 MW(e) KLT-40S barge-mounted 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 in the detailed design stage. It is an integral pressurized LWR with natural circulation of the primary coolant. The 8.6 MW(e) RITM-200, currently in the detailed design phase, is an integral reactor with forced circulation for nuclear icebreakers. The Russian Federation also plans to construct several SVBR-100 units in 2013. The SVBR-100 is an innovative small modular fast reactor with lead–bismuth eutectic (LBE) alloy as the coolant and a power output of 100 MW(e).

In the USA, four integral pressurized water SMRs are under development: mPower, NuScale, Westinghouse's SMR and Holtec's SMR-160. The mPower consists of 2–6 180 MW(e) modules. NuScale Power envisages a nuclear power plant of up to twelve 45 MW(e) modules. The Westinghouse SMR is a conceptual 225 MW(e) design incorporating passive safety systems and proven components of the AP-1000. Development has also started on a more recent SMR design, Holtec's SMR-160, a 160 MW(e) reactor that relies on natural convection, thereby eliminating the need for coolant pumps and dependence on external power sources. GE Hitachi is developing PRISM, a 311 MW(e) liquid metal cooled fast breeder reactor that features an underground containment on seismic isolators with a passive air cooled ultimate heat sink.

In India, the 304 MW(e) advanced heavy water reactor (AHWR) being developed by the Bhabha Atomic Research Centre (BARC) is in the detailed design phase. It will use LEU and thorium mixed oxide (MOX) fuel and incorporate vertical pressure tubes and passive engineered safety features. The 500 MW(e) Prototype Fast Breeder Reactor (PFBR-500) is in the final stage of construction at Kalpakkam. Startup commissioning is planned for the first quarter of 2013. India also has four 700 MW(e) PHWRs and one 500 MW(e) FBR currently under construction.

Although electricity production is by far the principal function of today's operating reactors, a number of them are also currently used for desalination, process heat and district heating (Fig. A-4). Additional possible future non-electric uses include hydrogen production to (a) upgrade low quality petroleum resources such as oil sands while offsetting carbon emissions associated with steam methane reforming; (b) support large scale production of synthetic liquid fuels based on biomass, coal or other carbon sources; (c) serve directly as a vehicle fuel, most likely for light duty plug-in hybrid hydrogen fuel cell vehicles.

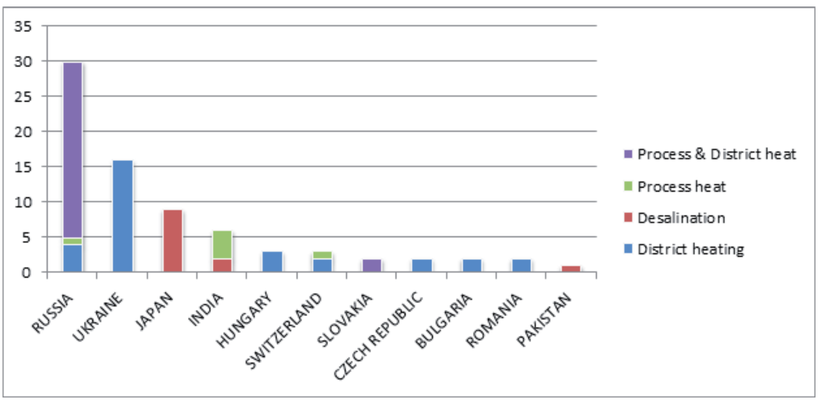

FIG. A-4. Number of reactors currently used for non-electric purposes as well as electricity production.

A.2. The future of nuclear power

The Fukushima Daiichi accident is expected to slow or delay the growth of nuclear power, but not to reverse it. The IAEA publishes two updated projections annually for the global growth in nuclear power: a low projection and a high projection. The 2012 updates for both the high and low projections show growth in nuclear power capacity, by 23% by 2030 in the low projection and by 100% in the high projection. However, the growth rate is slower than that projected in 2011, particularly in the low projection.

The high projection assumes that the current financial and economic crises will be overcome relatively soon and past rates of economic growth and electricity demand will resume, notably in the Far East. It also assumes stringent global policies to mitigate climate change. The low projection assumes that current trends will continue with few changes in policies affecting nuclear power. It does not assume that all national targets for nuclear power will be achieved. It is a ‘conservative but plausible’ projection. The projections are made at a regional, rather than national, level. The 2012 low projection takes into account a potential decline of the share of nuclear power in Japan’s electricity mix.

In the low projection, the world’s installed nuclear power capacity grows to 456 GW(e) in 2030, a 9% reduction in the level projected the previous year. In the updated high projection, it grows to 740 GW(e) in 2030, an increase that is approximately 1% less than that projected in 2011. Relative to previous projections that did not take into account the Fukushima Daiichi accident, the low projection has been reduced by 16% while a more moderate 8% decrease is seen in the high projection. The low projection shows a ten year delay compared to pre-Fukushima anticipated growth; the capacity that before the accident was projected for 2020 is now being projected for 2030.

Most of the growth will occur in regions that already have operating nuclear power plants. Projected growth is strongest in the Far East — from 83 GW(e) at the end of 2012, capacity grows to 153 GW(e) in 2030 in the low projection and to 274 GW(e) in the high projection. Western Europe shows the biggest difference between the low and high projections. In the low projection, Western Europe’s nuclear power capacity drops from 114 GW(e) at the end of 2012 to 70 GW(e) in 2030. In the high projection, nuclear power grows to 126 GW(e). In North America, the low scenario projects a small decline, from 115 GW(e) at the end of 2012 to 111 GW(e) in 2030. The high projection projects an increase to 148 GW(e).

Other regions with substantial nuclear power programmes are Eastern Europe and the Middle East and South Asia. Nuclear power expands in these regions in both the low and high projections — to levels 2–4 GW(e) below those projected before the accident.

The International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD) also publishes projections of the global growth in nuclear power. According to the IEA’s World Energy Outlook 2012, under its central scenario, referred to as the New Policies Scenario, global nuclear generating capacity will reach some 550 GW(e) in 2030. This is some 7% less than the IEA forecast a year ago and is comparable to the similar decrease seen in the IAEA’s low projection when compared to its previous edition.

Nuclear power and sustainable development

Energy plays a central role in achieving sustainable development goals. The choices countries will make in the coming years with regard to fuels and energy technologies may greatly determine how fast the world can move to a sustainable future. A major international conference, the United Nations Conference on Sustainable Development (also commonly referred to as Rio+20), was held in June 2012 in Rio de Janeiro, Brazil, to review the progress made in sustainable development since the United Nations Conference on Environment and Development (Earth Summit) in 1992 and to outline a path for future actions at the national, regional and global levels. The Rio+20 outcome document, The Future We Want, elaborates a development path covering a spectrum of individual and collective choices and addresses several priority issues, including the provision of access to clean energy for everyone, and ensuring that the energy produced does not contribute to climate change.

In November–December 2012, the 18th session of the Conference of the Parties to the UN Framework Convention on Climate Change (COP-18) took place in Doha, Qatar, together with the 8th session of the Conference of the Parties to the Kyoto Protocol. The Parties to the Kyoto Protocol agreed to a second commitment period from 2013 to 2020. Without this commitment, the world would have had no international agreement limiting greenhouse gas (GHG) emissions, and without limits on GHG emissions, nuclear power's very low emissions have no economic value. National or regional laws limiting emissions (as in the EU) would have remained, but progress toward stricter, more comprehensive limits would have been reversed.

Designing appropriate national energy strategies to meet developmental needs and to provide sustainable modern energy services for all is becoming increasingly complex due to the growing number of factors influencing energy choices. Firstly, it requires a comprehensive evaluation of all possible energy supply and demand options in terms of social, economic and environmental impacts. Many Member States, particularly developing countries, lack local expertise and experience to undertake such a task and the IAEA has been providing technical support to help build local expertise to fill this gap. Secondly, low carbon sources of energy, such as nuclear energy, minimize the GHGs emitted by energy generation and mitigate the negative impact of climatic disruption on development.

When studying their energy choices, a significant number of countries are considering nuclear power as an option. The factors contributing to the continuing interest in nuclear power include the increasing global demand for energy, as well as concerns about climate change, volatile fossil fuel prices and security of energy supply.

Figure A-5 compares the IAEA's 2012 projections, the IEA's 2012 scenarios, and 2011 projections by the World Nuclear Association (WNA). The high scenarios from the three organizations produce similar results, as do the low nuclear scenarios of the IAEA and the IEA.

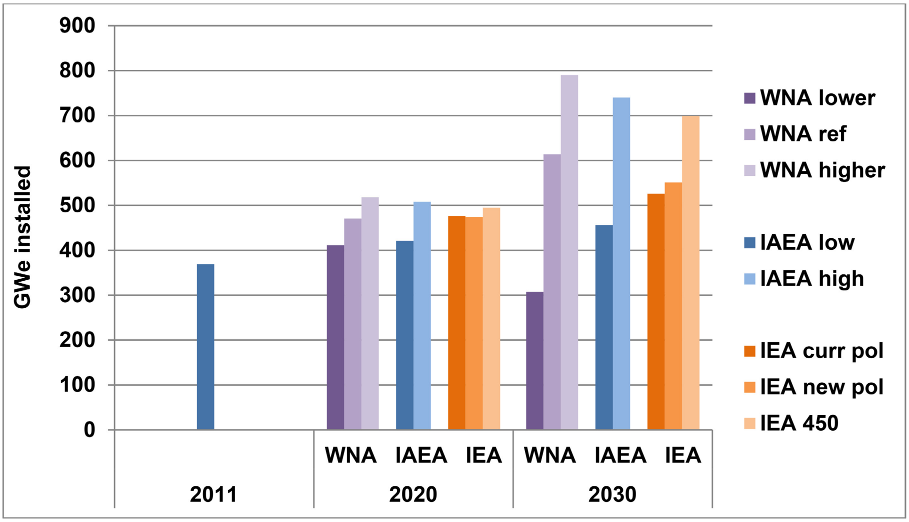

FIG. A-5. Comparison of nuclear power projections from the IAEA (blue), the World Nuclear Association's 2011 report on The Global Nuclear Fuel Market (WNA; purple) and the International Energy Agency's World Energy Outlook 2012 (IEA; orange).

A.3. Fuel cycle[2]

A.3.1. Uranium resources and production

In 2012, the IAEA and the OECD/NEA published the latest edition of the 'Red Book', Uranium 2011: Resources, Production and Demand. It estimated the total identified amount of conventional uranium resources, recoverable at a cost of less than $130/kg U, at 5.3 million tonnes of uranium (Mt U). This is 1.4% less than the estimate from the previous edition (published in 2010). In addition, there were an estimated 1.8 Mt U of identified conventional resources recoverable at costs of between $130/kg U and $260/kg U, bringing total identified resources

[2] More detailed information on IAEA activities related to the nuclear fuel cycle is available in the relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2012) and at www.iaea.org/NuclearFuelCycleAndWaste.

recoverable at a cost of less than $260/kg U to 7.1 Mt U. The spot price for uranium, after a two year high in early 2011, fell after the Fukushima Daiichi accident and ended the year at $135/kg U. By the second half of 2012, spot prices had dropped to around $110/kg U owing to uncertainty surrounding Japan's nuclear programme, but ended the year at around $115/Kg U. However, long term prices for uranium remained steady at around $158 /kg U.

Total undiscovered resources (prognosticated and speculative resources) reported in the 'Red Book' amounted to more than 10.43 Mt U, increasing slightly from the 10.40 Mt U reported in the book's previous edition. Undiscovered conventional resources were estimated at over 6.2 Mt U at a cost of less than $130/kg U, with an additional 0.46 Mt U at costs of between $130/kg U and $260/kg U. There were also an estimated additional 3.7 Mt U of speculative resources for which production costs had not been specified.

Additional resources were reported in 2011 for many uranium deposits in Africa — namely in Botswana, Malawi, Mali, Mauritania, Namibia, the United Republic of Tanzania and Zambia — where uranium exploration efforts remained strong. A feasibility study is being undertaken for the Mkuju River project in the United Republic of Tanzania. UNESCO's World Heritage Committee approved a boundary change to the Selous Reserve of Tanzania in a step towards developing the Mkuju River uranium site. However, the potential mine remains subject to a mining licence application by the company Uranium One. Additional or new resources were also reported in 2012 for Colombia, Guyana, Paraguay, Peru and Sweden.

Unconventional uranium resources and thorium further expand the resource base. Unconventional resources include potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonatite, black schist and lignite, resources from which uranium is only recoverable as a minor by-product, as well as uranium in seawater. Very few countries currently report unconventional uranium resources. Current estimates of potentially recoverable uranium are of the order of 8 Mt U. Uranium Equities announced that its portable demonstration plant for the recovery of uranium from phosphoric acid using an ion exchange technique (PhosEnergy Process) began tests in June 2012. In September 2012, it was announced that the test operations had been successful with over 90% recovery of uranium during the process. An engineering study of the PhosEnergy Process has been commissioned.

The Government of Finland granted a licence in March 2012 for the extraction of uranium as a by-product from the Talvivaara nickel mine operated by the Talvivaara Mining Company in Sotkamo, eastern Finland (Fig. A-6). An environmental permit from the Northern Finland Regional State Administrative Agency and a startup permit from the Radiation and Nuclear Safety Authority are still required for the start of uranium production. Cameco Corporation

FIG. A-6. Talvivaara uranium project, Finland.

is providing technical assistance to Talvivaara in the design, construction, commissioning and operation of the uranium extraction circuit. Unconventional resources are 22 000 t U.

Worldwide resources of thorium are estimated to be about six to seven million tonnes. Although thorium has been used as fuel on a demonstration basis, substantial further work is still needed before it can be considered as an alternative to uranium. In Canada, Candu Energy signed an agreement with three subsidiaries of the CNNC in August 2012 to expand their cooperation in the development of thorium and recycled uranium as alternative fuels for new CANDU reactors. The agreement marks the third phase of cooperation between Canada and China, which began in 2008.

Seawater has been investigated extensively as an unconventional source of uranium. In the USA, the Oak Ridge National Laboratory reported the development of new adsorbent materials. Mats made from 'HiCap' fibres, featuring high surface areas, are irradiated and then reacted with chemical compounds that have an affinity for uranium. The fibres delivered five times higher adsorption capacity, faster uptake and higher selectivity. Scientists at the University of Alabama are experimenting with the use of fibres based on chitin, a long chain biopolymer which can be obtained from shrimp shells.

Data on worldwide exploration and mine development expenditures up to and including 2010 are reported in the 'Red Book'. They totalled $2.076 billion in 2010, an increase of 22% compared to the 2008 figures reported in the book's previous edition.

Uranium production in 2010, the most recent year reported in the 'Red Book', was 54 670 t U (Fig. A-7). Australia, Canada and Kazakhstan accounted for 62% of this production. These three countries, plus Namibia, Niger, the Russian Federation, the USA and Uzbekistan, accounted for 92%. The WNA estimates that production was 54 610 t U in 2011 and 52 222 t U in 2012.

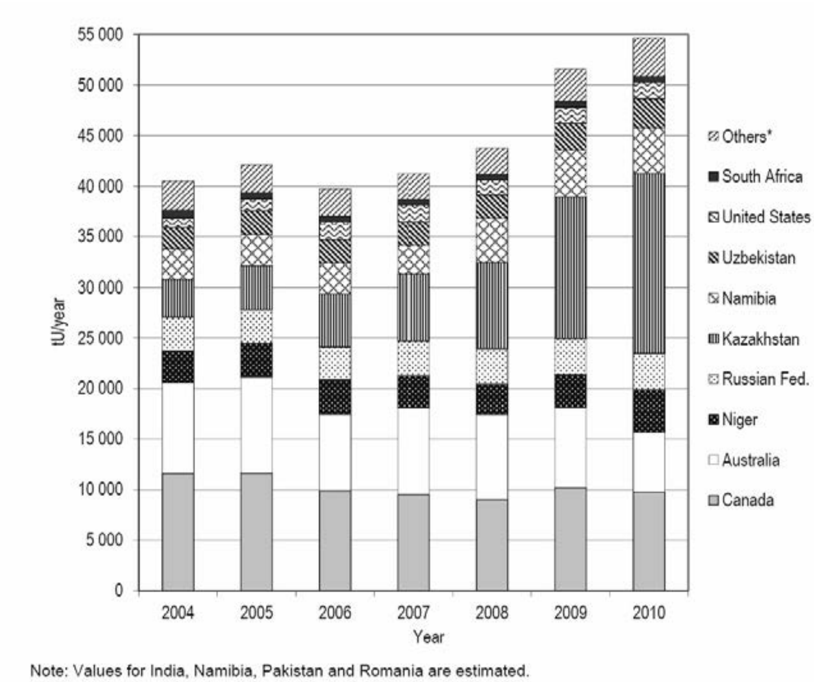

FIG. A-7. Recent world uranium production (Source: Uranium 2011: Resources, Production and Demand).

In situ leaching (ISL)[3] surpassed underground mining as the main production method in 2009 and the proportion of ISL production in world totals is expected to continue to increase in the future. In 2012, there were expansions at several ISL mines in Kazakhstan which have increased production in the country by approximately 2 250 t U annually.

Only a few uranium mines have started production in recent years (for example, in Australia in 2011 and in Niger in 2010). Construction of an ISL production centre has been in progress at Khiagda, Russian Federation, since 2010. The rail infrastructure has been modernized, and a new processing plant and sulphuric acid production facilities have been completed. The centre should be capable of producing 1 800 t U annually by 2018. In Namibia, the Stage 3 expansion at Paladin's Langer Heinrich mine was completed in 2012 to increase annual production to 2 000 t U. Stage 4 expansion will further increase annual production to 3 900 t U. Because of current market conditions, Areva has put on hold its development of the Trekkopje mine in Namibia.

In Australia, a ban which had prevented uranium mining in Queensland since 1982, when the Mary Kathleen mine ceased production, was lifted by the government of the province in October 2012. In South Australia, Quasar Resources announced that they will commence ISL mining operations at the Four Mile East and West deposits in 2013. In August 2012, BHP Billiton announced that it will investigate an alternative, less capital intensive design of the Olympic Dam open pit mine expansion in order to improve the economics of the project. As a result, the company was unable to approve an expansion of Olympic Dam before the indenture agreement deadline of 15 December 2012. In Western Australia, Toro Energy's Wiluna uranium mine received the state government's final environmental approval.

In Canada, AREVA Resources received environmental approval in August 2012 for its Midwest deposit project. This project involves the development of an open pit mine, a dedicated haul road linking the Midwest development with the existing McClean Lake operation and increasing the production capacity of the JEB mill at McClean Lake to accommodate the planned rate for milling of the Midwest ore.

In the USA, construction for Uranerz Energy Corporation's Nichols Ranch ISL operations in Wyoming started in August 2012. Uranerz announced in November 2012 that it had all of the regulatory permits and licences needed

[3] Conventional, or underground mining involves removing ore from the ground, then processing it to remove the minerals being sought. ISL involves leaving the ore where it is in the ground and recovering the minerals from it by dissolving them using a leaching solution and pumping the solution to the surface where the minerals can be recovered from the solution. Consequently, there is limited surface disturbance and no tailings or waste rock generated.

to construct and operate the Nichols Ranch mine. In October 2012, final regulatory approval was received for Ur-Energy's Lost Creek uranium project. Also, Uranium Energy Corp obtained all the permits needed to proceed with development of its Goliad ISL uranium project in South Texas. However, an aquifer exemption[4] is still required before uranium recovery activities can be initiated.

Uranium production in 2012 is estimated to have covered only about 77% of the estimated uranium consumption in reactors of 67 990 t U[5]. The remainder was covered by five secondary sources: military stockpiles of natural uranium, stockpiles of enriched uranium, reprocessed uranium from spent fuel, MOX fuel with uranium-235 partially replaced by plutonium from reprocessed spent fuel and re-enrichment of depleted uranium tails. At the estimated 2012 rate of consumption, the lifetime of 5.3 Mt U would be 78 years. This compares favourably to reserves of 30–50 years for other commodities (e.g. copper, zinc, oil and natural gas).

A.3.2. Conversion, enrichment and fuel fabrication

Six countries (Canada, China, France, Russian Federation, UK and USA) operate commercial scale plants for the conversion of triuranium octaoxide (U_3O_8) to uranium hexafluoride (UF_6), and small conversion facilities are in operation in Argentina, Brazil, the Islamic Republic of Iran, Japan and Pakistan. A dry fluoride volatility process is used only in the USA, while all other converters use a wet process. Total world annual conversion capacity has remained constant at around 76 000 tonnes of natural uranium (t U as UF_6) per year. However, major changes are expected with new plants being built in France (AREVA's Comurhex II (Fig. A-8)) and the USA (the Honeywell Metropolis Works plant). Total current demand for conversion services (assuming an enrichment tails assay[6] of 0.25% uranium-235) is in the range of 60 000–64 000 tonnes per year. A new conversion

[4] An important component of the USA's Federal Safe Drinking Water Act is the legal authority that allows ISL mineral development in portions of geological strata which are also shared by drinking water supplies. The US Environmental Protection Agency must issue an aquifer exemption for each mine site before any ISL recovery can occur.

[5] World Nuclear Power Reactors & Uranium Requirements, April 2012 (http://world-nuclear.org/info/reactors0412.html). Accessed 7 May 2012.

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

FIG. A-8. COMURHEX II conversion facility under construction in France. Gradual startup is expected in 2013–14.

facility in Kazakhstan, a joint venture between Kazatomprom and Cameco of Canada, the Ulba Conversion is expected to start construction by 2018. The facility will be co-located in the Ulba Metallurgical Plant in Ust-Kamenogorsk. The production capacity is expected to be 12 000 t UF_6 per year.

Total global enrichment capacity is currently about 65 million separative work units (SWUs) per year, compared to a total demand of approximately 45 million SWUs/year. Commercial scale plants operate in China (CNNC), France (AREVA), the Russian Federation (State Atomic Energy Corporation "Rosatom") and the USA (USEC and the URENCO Group). The URENCO Group operates centrifuge plants in Germany, the Netherlands, the UK (Fig. A-9) and the USA. There are also small enrichment facilities in Argentina, Brazil, India, the Islamic Republic of Iran, Japan and Pakistan.

FIG. A-9. URENCO Enrichment facility, Capenhurst, United Kingdom

Two new commercial scale enrichment facilities using centrifuge enrichment, both located in the USA, are under development: the AREVA Eagle Rock facility and the American Centrifuge Plant. A licence was issued in September 2012 for the construction of a full scale laser enrichment facility in North Carolina, USA, to be built by GE Hitachi subsidiary Global Laser Enrichment. The plant is expected to be capable of producing six million SWUs/year and of enriching uranium up to 8% uranium-235 by weight.

Argentina is rebuilding its gaseous diffusion capacity at Pilcaniyeu. Enrichment services are currently being imported from the USA.

In France, EURODIF's Georges Besse Gas Diffusion plant, operational since 1979, was closed in June 2012. Georges Besse II Uranium Enrichment Plant, at the same location, but with a different ownership profile, replaces this plant. It has a current installed capacity of 1.5 million SWUs/year with planned increases to 7.5 million SWUs by 2016. AREVA is the major shareholder in both operations.

Japan Nuclear Fuel Limited (JNFL) began the commercial operation of improved centrifuge cascades at Rokkasho, Aomori Prefecture, in March 2012. The planned expansion of the current capacity of 150 000 SWUs/year to 1.5 million SWUs/year and a new enrichment plant in Japan using Russian centrifuge technology under an agreement between Rosatom and Toshiba are being discussed.

Current total world deconversion[7] capacity in 2012 has remained at about 60 000 t UF_6/year.

In the USA, the NRC issued a licence in October 2012 to International Isotopes Fluorine Products for the construction and operation of a depleted uranium deconversion facility in New Mexico. The facility, to be known as the Fluorine Extraction Process and Depleted Uranium Deconversion Plant (FEP/DUP), will use the company's patented fluorine extraction process.

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

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

In China, production capacity for CNNC's fuel plant at Yibin was about 600 t U/year in 2012. As for the CNNC plant at Baotou, Mongolia, which fabricates fuel assemblies for Qinshan's CANDU PHWRs (200 t U/year), its fuel capacity is being expanded to 400 t U/year. A new plant is being set up in Baotou to fabricate fuel for China's AP1000 reactors. Furthermore, in 2012, the State Nuclear WEC Zirconium Hafnium Co. (SNZWH) started commissioning a new zirconium sponge production facility in Nantong, China. The new plant will produce the nuclear grade zirconium used to manufacture tubes for nuclear fuel assemblies, supplying both the Chinese market through SNWHZ and the global market through Westinghouse.

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

In Ukraine, the construction of a WWER-1000 fuel plant, with a planned capacity of 400 t U/year in 2015, has started near Smoline. The facility will be built by the TVEL Fuel Company as a joint venture between the Russian Federation and Ukraine, with 50% plus one shares belonging to the latter.

Recycling operations provide a secondary nuclear fuel supply through the use of reprocessed uranium (RepU) and MOX fuel. Currently, about 100 t of RepU/year is produced in Elektrostal, Russian Federation, for AREVA. One production line in AREVA's plant in Romans, France, manufactures about 80 t HM of RepU into fuel per year for LWRs in France. Current worldwide fabrication capacity for MOX fuel is around 250 t of heavy metal (HM), with the main facilities located in France, India and the UK 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 (RIAR) and in Ozersk at the Mayak Plant.

Elsewhere, MOX fuel is manufactured for use in LWRs. In the UK, the Sellafield MOX Plant was downrated from 128 to 40 t HM/year and, in August 2011, the Nuclear Decommissioning Authority announced that it had reassessed the plant's prospects and would close it. Additional MOX fuel fabrication facilities are under construction in the USA to use surplus weapons grade plutonium. Worldwide, approximately 30 LWRs currently use MOX fuel.

A.3.2.1. Assurance of supply

In December 2010, the Board of Governors approved the establishment of an IAEA LEU bank. During 2012, the IAEA's Secretariat continued work on the financial, legal and technical arrangements and site assessments for establishing the bank. It will be located at the Ulba Metallurgical Plant in Kazakhstan. Pledges in excess of $150 million have been made by Member States, the EU and the Nuclear Threat Initiative (NTI) for the establishment of the LEU bank. By the end of 2012, pledges had been fully paid by Norway ($5 million), Kuwait ($10 million), the USA (approximately $50 million) and the NTI ($50 million); the EU had paid €20 million of its pledged €25 million and arrangements were being finalized with the United Arab Emirates ($10 million).[8]

A.3.3. Back end of the nuclear fuel cycle

A.3.3.1. Spent nuclear fuel and nuclear fuel reprocessing

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

Notable developments in 2012, which will be elaborated briefly in the following paragraphs, include Posiva's application for a repository construction licence in Finland, Canada's suspension of its solicitation of communities interested in site selection for the Used Nuclear Fuel Repository and Centre of Expertise, because time was needed to respond fully to the 21 expressions of interest already submitted, and a report by the US Blue Ribbon Commission on America's Nuclear Future that recommended, among other things, a new consent based approach to siting the country's nuclear waste management facilities and a new organization dedicated solely to implementing the waste management programme. Implementing the Commission's recommendations will require significant changes in US legislation governing nuclear waste.

In 2012, about 10 000 t HM were discharged as spent fuel from all nuclear power reactors. The total cumulative amount of spent fuel that has been discharged globally up to December 2012 is approximately 360 500 t HM, of which about 250 700 t HM are stored in at-reactor or away-from-reactor storage facilities. Less than a third of the cumulative amount of spent fuel discharged

[8] Other assurance of supply mechanisms currently in place are described in the 2012 edition of the NTR.

globally, about 109 800 t HM, has already been reprocessed. In 2012, the global commercial reprocessing capacity, spread across four countries (France, India, the Russian Federation and the UK), was about 4800 t HM/year.

In December, Villar de Cañas was officially selected as the site to host a storage facility for Spain's used nuclear fuel (Fig. A-10). The site was considered suitable in terms of geology, seismology, meteorology, hydrology, site geometry and risk in relation to local population centres. The facility will accept transport casks of used nuclear fuel assemblies, currently stored at each of Spain's nuclear power plants, and vitrified wastes originating from the Vandellós nuclear power plant and currently stored in France.

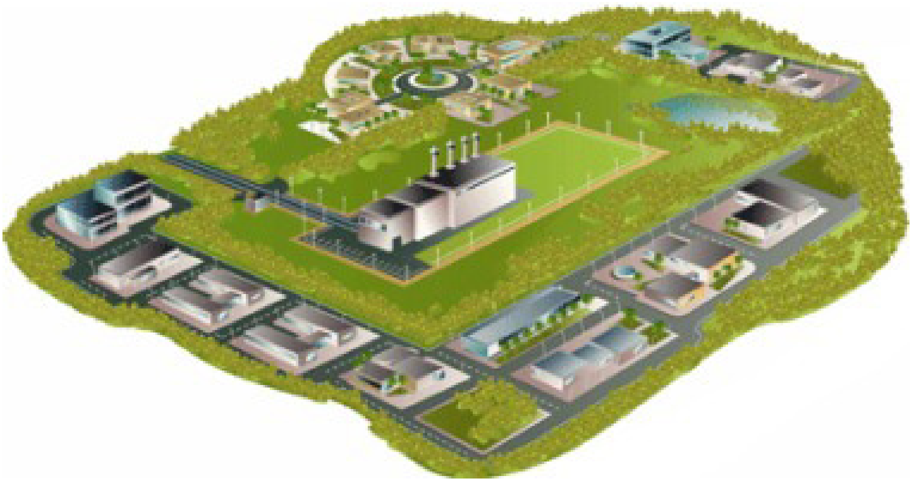

FIG. A-10. Visualization of the spent fuel storage facility to be built at Villar de Cañas.

In India, construction of the Fast Reactor Fuel Cycle Facility at Kalpakkam continues. The fabrication of MOX fuel pins for the upcoming prototype fast breeder reactor is currently being carried out at the Advanced Fuel Fabrication Facility of the Bhabha Atomic Research Centre at Tarapur.

In Japan, in September 2012 JNFL announced that it would proceed with construction of the 800 t HM/year commercial reprocessing plant at Rokkasho, which was suspended as a consequence of the earthquake and tsunami on 11 March 2011. Construction is scheduled to be completed in October 2013.

In the Republic of Korea, the Korea Atomic Energy Research Institute completed the construction of the PRIDE (Pyroprocess Integrated Inactive Demonstration) facility in July 2012 as part of an engineering scale demonstration facility for the pyroprocessing[9] of oxide spent fuels. The PRIDE facility startup tests commenced in August 2012 and are being followed by operational and functional performance tests of the operation and utility systems, planned to be completed in early 2013.

In the UK, the existing reprocessing contracts at the Thermal Oxide Reprocessing Plant (THORP) at Sellafield are expected to be completed by 2018. The Nuclear Decommissioning Authority has confirmed that the plant will then shut down for decommissioning rather than undertake the infrastructure development required to extend its life.

A.3.3.2. Radioactive waste management

Radioactive waste is produced from the use of nuclear technologies for energy production, research activities, medical and industrial applications, as well as from both legacy and current military use. The safe management of radioactive waste requires adequate storage capacities and ultimately requires disposal. Disposal facilities for all categories of radioactive waste are either operational or are under development worldwide. As of December 2012, 464 storage facilities and 154 waste disposal facilities were in operation worldwide[10] (Fig. A-11).

FIG. A-11. HABOG intermediate waste storage facility, The Netherlands.

[9] Pyroprocessing refers to non-aqueous methods of nuclear fuel reprocessing, where materials are extracted and refined without H_2O at high temperatures.

[10] Based on information provided by Member States to the IAEA's Net Enabled Waste Management Database (NEWMDB), accessible online at http://newmdb.iaea.org/.

Global inventory estimates

The global radioactive waste inventory reported as 'in storage' in 2011 (the most recent year available) was approximately 68 million cm^3 [11] (Table A-2). The cumulative amount of radioactive waste disposed of up to 2011 was approximately 76 million cm^3, which includes the deep well injection of some 29 million cm^3 of liquid waste, and disposal of approximately 4000 cm^3 of solid high level waste (HLW), primarily from Chernobyl. The annual accumulation of processed HLW is fairly constant, at an average accumulation rate of approximately 850 cm^3 per year worldwide (not including spent fuel).

National developments on disposal options

A large number of waste disposal facilities have been constructed and are being operated today for VLLW, LLW and ILW, and construction should start in the near future for some disposal facilities for spent nuclear fuel. Operating waste disposal facilities 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, USA); near surface engineered facilities for LLW (e.g. in China, the Czech Republic, France, India, Japan, Slovakia, Spain, the UK and Ukraine); subsurface engineered facilities for low and intermediate level waste (LILW) (e.g. in Sweden and Finland); borehole disposal of LLW carried out in the USA; and geological facilities to receive LILW (e.g. in Germany and USA). 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).

Disposal options for disused sealed radioactive sources (DSRSs) include co-disposal with other waste at suitable facilities, or disposal in dedicated boreholes, such as those under consideration in several countries including Ghana, Malaysia, the Philippines and South Africa.

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

In Belgium, the safety case developed by the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) for its planned near surface disposal at Dessel was the subject of an international peer review organized by the OECD/NEA; the conclusions of the review, released in September 2012, were positive overall.

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[11] Estimate developed using the IAEA's NEWMDB and other sources for countries that do not submit reports to the NEWMDB.

TABLE A-2. GLOBAL ESTIMATE OF RADIOACTIVE WASTE INVENTORY FOR 2011 (MOST RECENT DATA)[12]

Waste class	Storage[13] (m^3)	Cumulative disposal (m^3)
Very low level waste (VLLW)	153 000[14]	113 000
Low level waste (LLW)	56 663 000[15]	64 792 000[16]
Intermediate level waste (ILW)	8 723 000	10 587 000
High level waste (HLW)	2 743 000	72 000[17]

Sources: NEWMDB (2012), official national reports and publicly available data.

[12] 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: (a) mass and volume changes during the waste management process; (b) changes in reporting and changes or corrections made by Member States to their own data; and (c) the addition of new Member States to the database.

[13] 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.

[14] 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 Classification of Radioactive Waste (IAEA Safety Standards Series No. GSG-1, 2009), and therefore this estimate will probably become larger in the future, with a corresponding drop in the LLW category.

[15] The estimate for LLW in storage does not include approximately 4 × 108 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 Agency's definition of 'storage' as described in the IAEA Safety Glossary (2007). For this reason, the status of this waste is still indeterminate with respect to inclusion in this estimate.

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

[17] 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 clean-up of the accident at Unit 4 of the Chernobyl NPP.

In Canada, the development of three geological disposal facilities is being considered: the Bruce site facility for LLW and ILW from Ontario Power Generation, the Chalk River laboratories site for LLW and ILW, and a third site, as yet undefined, for Canada's Used Nuclear Fuel Repository and Centre of Expertise. The engineering and design work for the Bruce site facility is partially completed. Atomic Energy of Canada Limited is currently investigating the suitability of the Chalk River laboratories site. As for the third site, the 'expressions of interest' phase for communities wishing to engage in the site selection process for Canada's Used Nuclear Fuel Repository and Centre of Expertise was suspended by the country's Nuclear Waste Management Organization on 30 September 2012, in order to focus efforts on conducting the detailed studies required in communities that had already formally expressed an interest on or before that date.

China's medium term plan to manage its LILW is to have five regional disposal sites in operation by 2020 for a total disposal capacity of about 1 000 000 m^3. Two of these, located near Yumen in the north-west Gansu province and near the Daya Bay NPP in the southern Guangdong province, are in operation with current capacities of 20 000 m^3 and 80 000 m^3 respectively, with a potential for future expansion to 200 000 m^3 and 240 000 m^3. The third site, in south-western China, is under construction. Work on the two remaining sites in northern and eastern China has not yet started.

In Finland, Posiva is moving forward with the construction of the ONKALO underground research facility. In December, it submitted a repository construction licence application to the Finnish Government for the Olkiluoto site with the intention of commencing final disposal in 2020.

In France, the National Radioactive Waste Management Agency (Andra) is preparing the industrial phase of its reversible disposal project for ILW and HLW, Cigéo, to be commissioned in 2025, and has undertaken a feasibility review and a formalized public stakeholder engagement process prior to submitting a licence application. Andra has also published the 2012 edition of the national radioactive waste inventory, including characteristics, volume and localization of existing national wastes.

In Germany, the Government announced in November 2012 that all exploratory and survey work at the Gorleben atomic waste storage facility being conducted with the aim of making the temporary site permanent would stop until a political decision had been made as to the way forward for Gorleben: further exploration, moratorium or closure.

At the disposal facility at Bátaapáti, Hungary, which was designed to receive 40 000 m^3 of LILW from NPP operations, construction work has been completed for the inclined access ramps leading to the repository (Fig. A-12), the service tunnels, as well as the first two disposal vaults. At the opening ceremony in December, a first waste disposal package of nine waste drums encased in concrete was placed in the facility (Fig. A-13). The concept of operations provides for the parallel construction of further disposal vaults while the waste is placed in existing ones.

FIG. A-12. Access ramp to the national radioactive waste disposal facility at Bátaapáti, Hungary.

FIG. A-13. Emplacement of the first waste disposal package at the disposal facility in Bátaapáti, Hungary.

In the Republic of Korea, construction of the Gyeongju disposal facility, which is designed for the disposal of 100 000 drums of LILW in silos, is currently scheduled for completion in June 2014.

Lithuania's Radioactive Waste Management Agency has completed site investigations and is considering design options for a planned near surface disposal facility, with a capacity for disposal of approximately 100 000 m^3 of short lived LILW.

In the Russian Federation, the government approved three fundamental documents on radioactive waste management to support activities in the field of nuclear energy, cleanup works, remediation of contaminated sites and the extraction and processing of mineral and organic materials with a high content of natural radionuclides. Work on the creation of radioactive waste disposal facilities has also started. 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. The laboratory will study the possibility of disposal of long lived HLW and ILW at the site. The disposal facility is to start operations in 2021. In addition, preliminary design work (geological and engineering studies) has been performed for a disposal facility for LLW and short lived ILW in the north-west of the Russian Federation. The country's first commercial away-from-reactor dry storage facility began operation in 2011, the Mining and Chemical Complex Site, Dry Storage, Stage I, in Zheleznogorsk, Karasnoyarsk.

In June 2012, an OECD/NEA appointed international team concluded a positive review of the licence application for a geological disposal and encapsulation plant in Oskarshamn submitted by the Swedish Nuclear Fuel and Waste Management Company, which expects the plant to start operations by 2025.

Ukraine's LILW disposal facility at Buryakovka, developed following the Chernobyl accident, is scheduled for a capacity expansion of 120 000 m^3 from its current capacity of approximately 700 000 m^3, under a reconstruction project funded by the European Commission.

In the USA, a new radioactive waste disposal facility in Andrews County, Texas, began operations in April 2012. It accepts LLW from Texas, Vermont and the Federal Government. The shallow land trench type facility includes two adjacent repositories of similar design, one for commercial wastes and the other for Federal Government waste.

A number of successful operations have been conducted 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. With direct assistance from the IAEA, 125 DSRSs, including an old gamma irradiator, were recovered in Honduras and transferred to the national storage facility. Also with direct IAEA assistance, two gamma irradiators were recovered, decontaminated, characterized, packaged and transported from a contaminated bunker to an institution with safer storage conditions in Costa Rica in February 2012. To ensure safer long term storage, several disused radium-226 and caesium-137 brachytherapy sources were conditioned in Honduras and Costa Rica in November 2012. Furthermore, the repatriation of an Indian irradiator from Uruguay, which contained 15 disused high activity radioactive sources, was successfully completed in September 2012 with direct assistance from the IAEA, in cooperation with the US Nonproliferation and Disarmament Fund and the Global Threat Reduction Initiative (GTRI).

Legacy radioactive waste

Significant work is being carried out to eliminate the nuclear legacy of the Cold War. For over fifteen years, the IAEA's Contact Expert Group for International Nuclear Legacy Initiatives in the Russian Federation (CEG) has proved to be an efficient forum for information exchange and coordination of nuclear legacy programmes in the Russian Federation. In 2012, one of its most important achievements was the successful defuelling of a submarine reactor with liquid metal coolant in November. The Russian Federation, with significant help from CEG partners, has defuelled and dismantled the majority of 200 decommissioned nuclear submarines and there are only 5 left that have not yet been dismantled. The defuelled submarine reactor units are in the process of being sealed and placed in long term storage facilities. One of these facilities was completed in 2011 in the north-west of the Russian Federation. A second one was inaugurated in May 2012 in the far east of the Russian Federation and received its first reactor compartment for storage in September (Fig. A-14). A similar programme is being carried out in the USA, which has dismantled 114 nuclear submarines and ships.

The safe management and removal of spent nuclear fuel and waste from former navy bases is now the CEG's priority. Two regional radioactive waste conditioning and storage centres are under construction in the north-west and far east of the Russian Federation. An international programme for recovering powerful radioisotope thermoelectric generators (RTGs) that were used for navigation purposes (e.g. batteries for lighthouses) along the coastline of the Russian Federation is also being successfully implemented. The majority of the country's 1007 RTGs have now been recovered, with only 75 remaining.

FIG. A-14. Dismantling a nuclear submarine.

Radioactive waste management: addressing the Fukushima Daiichi accident

The Fukushima Daiichi accident created significant challenges related to the management of radioactive waste, located on-site as well as spread over a vast area off-site (Fig. A-15). On-site wastes include large volumes of highly contaminated salt water in reactor and turbine buildings and a variety of solid wastes such as debris, logged trees, soil and metal, containing mainly caesium radionuclides but also significant concentrations of other fission products and possibly traces of transuranics. Off-site wastes include the large volumes of contaminated debris from the destruction caused by the tsunami and very large volumes of contaminated material from planned massive cleanup/remediation activities in the urban, agriculture, forest and aquatic areas most affected by radioactive caesium releases (Fig. A-16).

Highly radioactive water that has accumulated in the reactor and turbine buildings is being continuously processed for the removal of caesium in purification facilities set up through local and international collaboration. The processed water has been stored in tanks or reused to cool the damaged reactor cores after desalination. The cumulative volume of processed water is approximately 500 000 m^3 as of November 2012. Multinuclide removal facilities to remove radioactive elements other than caesium have been installed and are being prepared for the start of operations. Major ongoing challenges in this area include the storage of very large volumes of processed water and the continuing ingress of groundwater into the buildings, resulting in ever increasing volumes of contaminated water to be processed and stored. Solid wastes accumulated

FIG. A-15. TEPCO's Fukushima Daiichi Nuclear Power Plant, October 2011.

FIG. A-16. Temporary storage of soil removed at a model remediation project at the Tominari elementary school, city of Date, October 2011.

at the site have been stored in temporary storage facilities and sampling and analysis are in progress to determine the wastes' characteristics and options for further management.

The removal of fuel debris from the damaged reactors ('defuelling') presents a number of technological challenges. This work will need to be done under extremely high radiation dosage conditions inside the reactor buildings. Hence, the defuelling will require the development and deployment of special tools, the remote handling of equipment and the use of advanced techniques. Remotely controlled devices for the careful examination of contamination status or remotely operated and robotic technologies for decontamination activities (e.g. washing, cleaning/vacuuming, brushing/surface-chipping, and painting/spraying of decontamination agents) will need to be developed to prevent unnecessary exposure of workers. Research and development for such devices and technologies is planned through multilateral collaboration among international experts and institutions.

The 2011 Act on Special Measures Concerning the Handling of Radioactive Pollution came fully into force on 1 January 2012 in Japan. Based on this act, the planning and implementation of off-site decontamination, as well as the collection, transfer, temporary storage and final disposal of the wastes, are being carried out. Decontamination is being carried out in a total of 104 municipalities. This includes areas within 20 km of the Fukushima Daiichi nuclear power plant or areas where the annual radiation dose exposure exceeds 20 mSv. As of August 2012, 78 out of 104 municipalities had completed their decontamination. Also, intensive efforts to secure an interim storage facility were being made, with the objective of finding a location for a facility within a year and starting operations within three years. Final disposal is expected to be carried out within 30 years from the start of the interim storage.

A.3.3.3. Decommissioning

As of December 2012, 142 power reactors worldwide had been permanently shut down. This includes 18 power reactors that were either declared as entering the decommissioning phase or that were permanently shut down in 2012. In total, 16 power reactors have now been fully dismantled, a further 52 reactors are in the process of being dismantled, 59 are being kept in a safe enclosure mode or are awaiting commencement of final dismantling, 3 are entombed, and 12 do not yet have a specified decommissioning strategy.

More than four hundred research reactors and critical assemblies are now decommissioned or are in the process of being dismantled. Several hundred other nuclear facilities, such as radioactive waste management or nuclear fuel cycle facilities, have been decommissioned or are undergoing dismantling.

Significant progress has been made in the implementation of power reactor decommissioning projects in France, Spain, the UK, Ukraine and the USA. The dismantling of reactor internals[18] at José Cabrera NPP in Spain and the ongoing assembly of the new safe confinement for the fourth unit of the Chernobyl NPP are examples of technical achievements (Figs. A-17 and A-18). Nevertheless, despite the progress in several countries, the implementation of decommissioning projects needs to be accelerated in some Member States with less developed nuclear infrastructures.

FIG. A-17. The dismantling of reactor internals (left) at the Jose Cabrera Nuclear Power Plant (right) (Photograph courtesy of ENRESA).

FIG. A-18. The assembly of the new safe confinement for the fourth unit at the Chernobyl NPP (Photograph courtesy of Chernobyl NPP).

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[18] 'Nuclear reactor internals' are major structures within a reactor vessel which have one or more functions such as supporting the core, maintaining fuel alignment, directing primary coolant flow, providing radiation shields for the reactor vessel, and guiding in-core instrumentation.

Considerable decommissioning challenges remain, such as the availability of funding and waste disposal options, together with access to appropriate technical and human resources, especially in the case of NPPs that have been shut down after a severe accident. The ongoing decommissioning of the Chernobyl NPP and the future decommissioning of the Fukushima Daiichi nuclear power plant are the most visible examples of such nuclear facilities. The lack of an appropriate legal and regulatory framework also remains an important constraint in some countries.

In Japan, the mid and long term roadmap for the decommissioning of the Fukushima Daiichi nuclear power plant was updated in August 2012. The Progress Status of Mid-and-long Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Units 1–4, TEPCO,[19] released by the Nuclear Emergency Response Headquarters Government–TEPCO and Long-Term Response Council, was drafted to describe the framework of all activities required for the decommissioning of the plant and its related radioactive waste management (Fig. A-19).

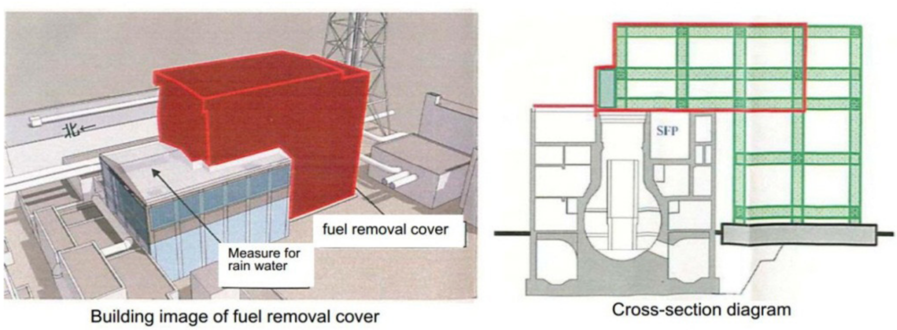

FIG. A-19. Protection cover for the removal of spent fuel from the spent fuel pool at Fukushima Daiichi.

A.4. Safety

In 2012, discussions of nuclear power plant safety focused largely on identifying and applying the lessons that could be learned from the March 2011 Fukushima Daiichi nuclear accident. Although there are lessons yet to be learned, action plans applying the preliminary lessons learned from the accident have

[19] http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20120625_01a.pdf

already been developed and are being implemented at both the national and international level. Adopted by the General Conference in September 2011, the IAEA Action Plan on Nuclear Safety defines a programme of work to strengthen the global nuclear safety framework. It defines 12 main actions.[20] Further lessons may be learned and, as appropriate, incorporated into these actions by updating the Action Plan.

In 2012, three Action Plan related international experts' meetings were convened by the IAEA: Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, in March, Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency, in June, and Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, in September. Furthermore, the Fukushima Ministerial Conference on Nuclear Safety was held from 15 to 17 December 2012 by Japan in co-sponsorship with the IAEA, and helped contribute to strengthening nuclear safety worldwide by sharing with the international community, at the ministerial and expert level, further knowledge and lessons learned from the Fukushima Daiichi nuclear accident.

Operationally, nuclear power plant safety around the world remains high, as indicated by safety indicators collected by the IAEA and the World Association of Nuclear Operators. Figure A-20 shows the total number of unplanned scrams, or shutdowns, per 7000 hours of critical power reactor operation. This is commonly used as an indicator of success in improving plant safety. As shown, steady improvements, although not as dramatic as those attained in the 1990s, 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 the Nuclear Safety Review for 2013 and in the IAEA Annual Report 2011.

[20] The text of the IAEA Action Plan on Nuclear Safety can be consulted at: http://www.iaea.org/About/Policy/GC/GC55/GC55Documents/English/gc55-14_en.pdf

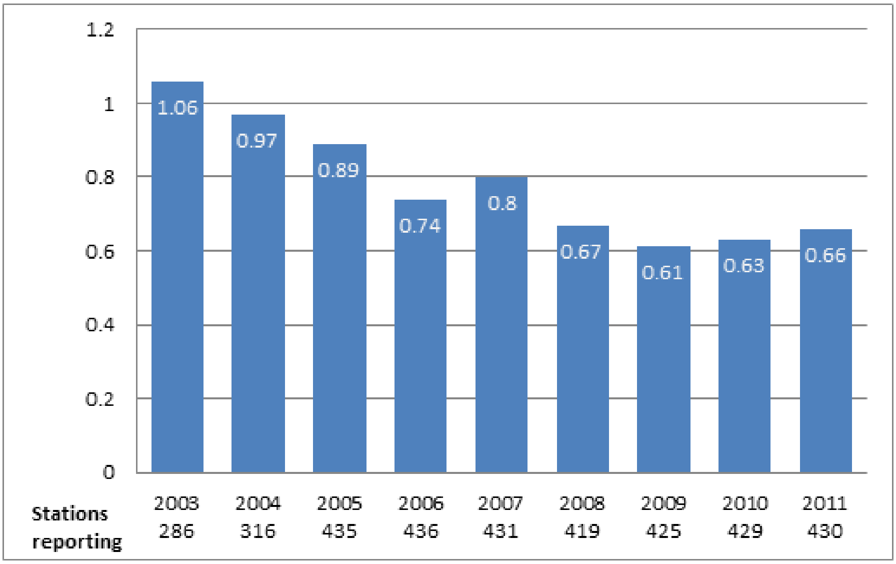

FIG. A-20. Total number of unplanned scrams, including both automatic and manual scrams, that occur per 7000 hours of critical power reactor operation. Source: IAEA's PRIS (Power Reactor Information System), http://www.iaea.org/pris.

B. ATOMIC AND NUCLEAR DATA[21]

Accurate nuclear and atomic data are crucial for all nuclear research and innovation. These data are essential for many applications such as nuclear power (fission), research reactors, nuclear fusion, medicine, non-destructive testing and environmental monitoring.

Nuclear data work is carried out worldwide by regional data centres. One of the core centres is located at the IAEA; others include the OECD/NEA Data Bank in Paris, France, the Nuclear Data Centre in Obninsk, Russian Federation, and the National Nuclear Data Center at the Brookhaven National Laboratory, USA. The IAEA coordinates two networks that link these centres, the International Network of Nuclear Reaction Data Centres (NRDC) and the International Network of Nuclear Structure and Decay Data Evaluators (NSDD). The NRDC primarily deals with the Experimental Nuclear Reaction Data (EXFOR) database while the NSDD oversees the Evaluated Nuclear Structure Data File (ENSDF) and undertakes relevant horizontal evaluations. These continuously updated databases provide essential input for research and development in nuclear science and technology, for both energy and non-energy applications.

Over the past year, a change in the format for the storage of nuclear data has been considered by the international data community. Current technical possibilities would allow for changing the standard from the current and long standing ‘punch card’ text format to a modern structured language such as XML. If agreed to, such a change would be a significant innovation.

The International Symposium on Reactor Dosimetry (ISRD-14), held in May 2011 in the USA, highlighted the importance of dosimetry data to enable neutron spectra and fluences to be accurately determined. While the IAEA’s International Reactor Dosimetry File (IRDF) database has provided such a standard for many years, this has recently been superseded by a new dosimetry file, the International Reactor Dosimetry and Fusion File (IRDFF), also produced by the IAEA, designed for a wider range of applications, including fusion. It is planned that IRDFF will be validated and improved as necessary over the next few years, in particular by work coordinated by the IAEA.

Evaluated data files are used as input by users in codes to design devices, produce safety cases and do basic science. During 2011 and 2012, three new versions of these files were released worldwide: ENDF/B-VII.1 (USA), JEFF-3.1.2 (Europe) and JENDL-4.0 (Japan). It is expected that, over the next few years, these files will be extensively validated and tested. This will help

[21] Starting with the NTR 2012, developments in advanced fission and fusion are covered on a biennial basis, in alternation with developments on atomic and nuclear data. This increased focus enables us to describe significant trends and developments in greater detail.

identify any defects and further experiments and calculations will be carried out to help produce improved versions of the files. Figure B-1 shows an example of data, including uncertainty, for the neutron capture reaction on tungsten from the three databases. This plot was produced by software developed by the IAEA to enable better visual comparisons and dissemination of nuclear data from a wide range of data sources.

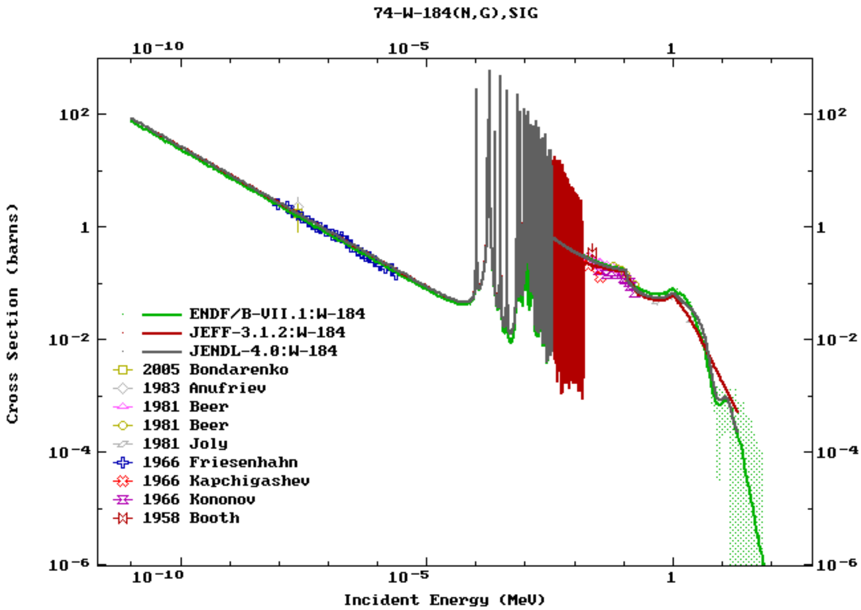

FIG. B-1. Example of data from three recent evaluated data libraries with a selection of experimental data from EXFOR included. The shaded region at the right shows how uncertainty information from ENDF/B-VII.1 can be represented.

The evaluated data files mentioned above are reaching a degree of maturity with much of the data converging. However, there remain several areas where deficiencies are recognized but these are typically of a scale difficult to resolve by a single evaluation project. International collaboration is seen as an answer and much has already been achieved by the OECD/NEA's nuclear data evaluation cooperation activities, which have published 30 reports. It has been proposed that this be significantly expanded by a new working paradigm to expedite evaluated nuclear reaction data advances called the Collaborative International Evaluated Library Organization. Initially, a series of six priority isotopes, namely ^{1}H, ^{16}O,

^{56}Fe, $^{235,238}U$ and ^{239}Pu will be considered. This is planned to provide definitive evaluations that can be adopted by all projects and, in the future, under the governance of international bodies such as the OECD/NEA and the IAEA, could address much wider areas of nuclear data.

Fusion is a major potential energy source. The International Thermonuclear Experimental Reactor (ITER) project[22] aims to demonstrate the scientific and technological feasibility and safety features of fusion energy for peaceful purposes. Under the project, a power station scale device is being constructed that is expected to demonstrate the feasibility of producing 500 MW of fusion energy (Fig. B-2). The FENDL-2.1 library acted as a reference data source for the design of ITER and the improved FENDL-3 library has been produced under an IAEA coordinated research project to help analyse results.

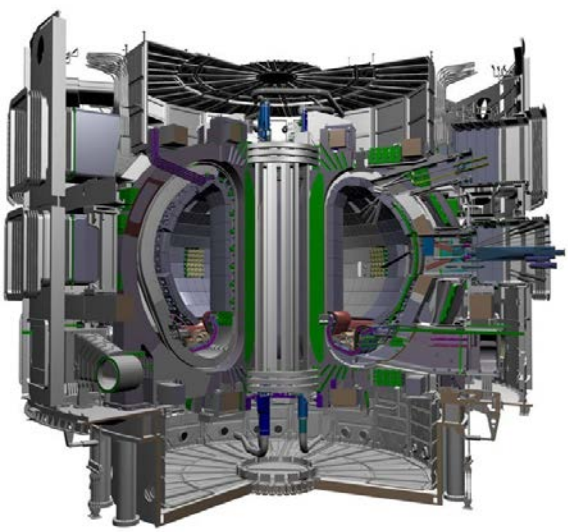

FIG. B-2. Cutaway view of the ITER device which is being built in France to investigate fusion energy production. Extensive amounts of nuclear and atomic data have been used in the design of the device and will be used to analyse its operation and experiments.

The 24th IAEA Fusion Energy Conference, held in October 2012 in San Diego, USA, attracted some 850 participants from 37 Member States and five international organizations. Approximately 700 papers were presented, including

[22] More information on ITER can be found at http://www.iter.org/.

results of the ITER-like wall experiment (Fig. B-3) on the Joint European Torus (JET) fusion device in the United Kingdom.

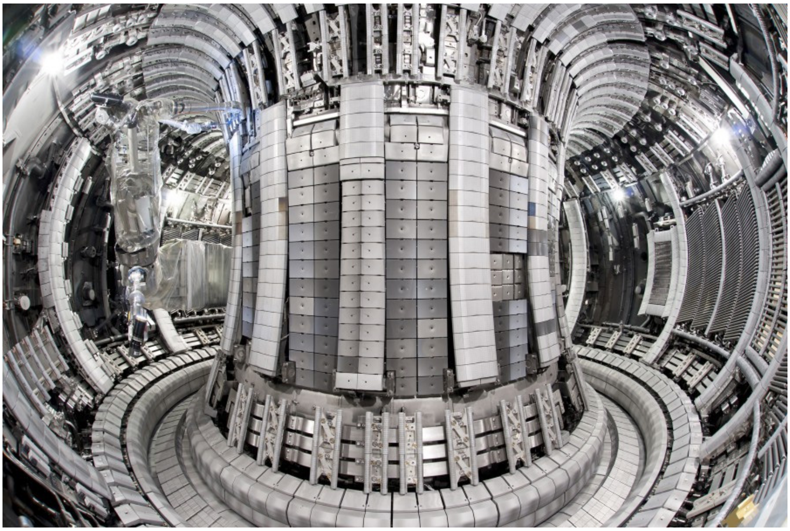

FIG. B-3. The inside of the JET vacuum vessel with the installation of the ITER-like wall completed.

Nuclear techniques for material analysis are becoming more prevalent, and methods formerly employed only in nuclear laboratories have been implemented by private industries as part of standard 'table top' equipment. Several international conferences are devoted to the subject. The 21st International Conference on Ion Beam Analysis (IBA) took place in Seattle, USA, on June 2013. The IAEA has completed a coordinated research project on the IBANDL database that provides data for IBA, and is implementing another on a related analytical technique, particle induced gamma ray emission.

New facilities that produce intense pulses of hard X rays are creating advances in atomic and molecular data. The Linac Coherent Light Source at Stanford in the USA was commissioned in 2009 and the SACLA facility at RIKEN Harima in Japan came on-line in 2011 and was opened to outside users in 2012. The X ray light from these facilities is used to illuminate targets ranging from individual atoms and molecules to living cells and nanocrystals. The high intensity and short pulse length make it possible to study matter under extreme conditions and to study complicated processes, for example in biomolecules, at the atomic level.

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in the USA involves 192 high-power lasers that focus ultraviolet light into a hohlraum where it is converted to X rays. In its initial phase of operation, 2009–2012, NIF has been dedicated to achieving net energy gain from heating and compressing a deuterium-tritium pellet. The predicted energy gain was not achieved and in part this points to the need for accurate atomic data for matter under extreme conditions. Operation of NIF continues.

The Virtual Atomic and Molecular Data Centre (VAMDC), a European information technology infrastructure project initially funded for 2009–2012, has succeeded in providing a common interface for some 20–25 databases for atomic and molecular data with applications in plasma physics and astrophysics. The interfaces and the associated query tools were built on the XML Schema for Atoms, Molecules and Solids (XSAMS), which was developed by an international team coordinated by the IAEA. Version 0.1 was released in 2009 and Version 1.0 was released in 2012. A follow-up project to VAMDC is under way.

Databases for atomic and molecular processes are increasingly based on computed data. In several recent meetings, the issue has been raised that computed cross-sections, like experimental cross-sections, have an uncertainty that must be quantified. The Joint IAEA-NFRI Technical Meeting on Data Evaluation for Atomic, Molecular and Plasma-Material Interaction Processes in Fusion was held in September 2012 in Daejeon, Korea, in order to review issues of error propagation and sensitivity analysis, the current status of evaluated databases, evaluation of theoretical and experimental data sets, evaluation methods and the role of semi-empirical fits. This first of its kind meeting has an important role in rejuvenating the international work on uncertainty assignment and data evaluation for atomic and molecular processes in fusion.

In 2013, the International Conference on Nuclear Data for Science and Technology will be held in New York, USA. The conference will showcase the work of scientists and engineers involved in the production or use of nuclear data for numerous applications.

C. ACCELERATORS AND RESEARCH REACTORS

C.1. Accelerators

Electrons, protons and other kinds of charged particles are accelerated to produce X rays, neutrons, charged particle beams and radioisotopes for use in research and technology. Accelerator based technologies are regarded as a key element to serve social and economic development with a wide variety of applications in the energy, health, agriculture, environment, materials, natural resources and education sectors.

Accelerators of many different designs have been developed. They may vary in size, with some small enough to fit on a table while others may be tens of kilometres long. Accelerators may have a linear or a circular shape. They may produce or accelerate beams of charged particles in pulses or continuously by utilizing different techniques. Accelerators are the main tools of a large variety of nuclear physics based applications of important societal impact, such as: the production of radioisotopes such as fluorine-18, copper-64, carbon-11 etc. for the preparation of radiopharmaceuticals used in the diagnosis of cancers; direct use of accelerator beams for the treatment of cancer; mineral and oil prospecting; processing semiconductor chips; sterilization of medical equipment and food products; artefact dating; and many others. Accelerators are continuously explored for novel applications and a notable development has been the successful use of the medical cyclotron for the production of technetium-99m, the most widely used diagnostic radionuclide in the world.

C.1.1. Material characterization

Nuclear technology plays a key role in the development of novel materials. Ion beam analysis (IBA) is an important tool to characterize the properties and performance of materials in areas such as archaeology, biomedicine, environmental pollution monitoring, food and agriculture, forensic science, industry, mining, the study of cultural heritage objects, etc. IBA techniques are usually non-destructive; however, the properties of the materials can be strongly affected by ion irradiation.

There are environmental concerns linked with the long half-life radioisotopes generated from nuclear fission at the back end of the nuclear fuel cycle. These have led to increased research and development efforts in developing a technology to reduce the amount of radioactive waste through transmutation[23] in either fast fission reactors or accelerator driven systems, including at the IAEA, where a number of initiatives are being implemented within the Technology Advances in Fast Reactors and Accelerator Driven Systems project.

Real time material characterization using synchrotron radiation, neutron, ion and electron beams is a valuable tool to address existing research and technological challenges to using certain materials in energy related applications. A better understanding of factors resulting from either the use or from ageing that degrade a material's performance can help address these challenges. The development of more sophisticated materials, for example, of materials that minimize energy consumption, may help alleviate the pressure on the earth's natural resources and limit environmental pressures. Accelerated particles can play an important role in developing these new materials: ions from ion beam accelerators can be used to simulate the radiation damage the material suffers in a fission or fusion reactor; they can also be used to create new materials through ion implantation; finally they can be used to analyse those materials. The created samples of new materials are small, hence referred to as 'model materials'. For cost effectiveness, once these materials have been manufactured, it is necessary to develop alternate and simpler methods to produce them. In situ and real time characterization of the manufacturing process can facilitate this by promoting a better understanding of all the steps needed.

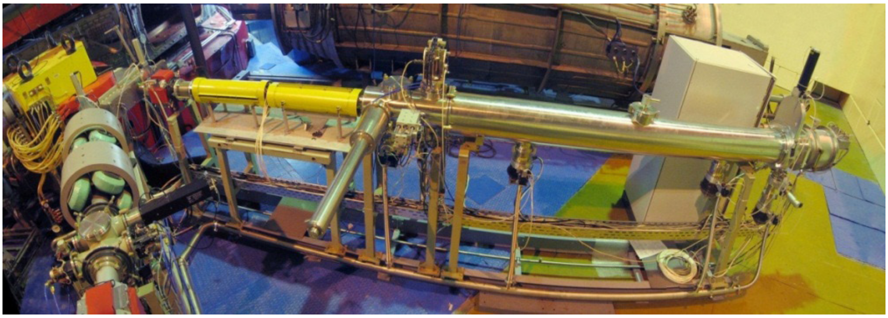

FIG. C-1. Development of a new ion beamline for radiation hardness testing of electronic devices at the U400M cyclotron facility in the Joint Institute for Nuclear Research (Russian Federation).

[23] The conversion of one element into another. Transmutation is under study as a means of converting longer lived radionuclides into shorter lived or stable radionuclides.

C.1.2. Elemental and molecular imaging with ion beams

Over the years, secondary ion mass spectrometry (SIMS) has developed into a powerful analytical tool for elemental analysis, particularly in materials such as semiconductors. Recently, this tool has been utilized to make high resolution molecular concentration images (maps) of surfaces, with lateral resolution of less than one micron. New developments in the depth profiling of molecular materials may ultimately provide a complete 3-D image of the analysed material. However, a drawback to this technique is that the analysis must be performed in a vacuum. The atmospheric pressure mass spectrometry techniques that are currently available, including those based on matrix-assisted laser desorption/ionization (MALDI), direct analysis in real time (DART) and desorption electrospray ionization (DESI), have varied ranges of spatial resolution, as illustrated in Table C-1. Detection limits can also be affected by, among other things, the choice of solvent used. Another drawback is the fact that some techniques may destroy molecular information. To date, no mass spectrometry technique is capable of providing high mass molecular maps in ambient pressure conditions with high spatial resolution.

Megaelectronvolt secondary ion mass spectrometry (MeV-SIMS) has recently emerged as a technique that can yield chemical as well as elemental information. This method employs heavy ions in the MeV energy range accelerated by ion accelerators and focused in a nuclear microprobe facility. Secondary molecular ions, emitted from the irradiated surface of the sample, are detected using the time-of-flight (ToF) method. Promising applications of MeV-SIMS are foreseen in the mapping of organic molecules, especially in biomedical, cultural heritage and forensics research.

It is possible to extract MeV ions from the vacuum system and into air through a thin window. This technique has been used extensively in the past to perform elemental analysis of objects in ambient conditions using conventional ion beam analysis techniques. A number of key areas would benefit from a high resolution ambient pressure molecular imaging system. These include: archaeometry, geological and environmental sciences, forensics and biomedical sciences. A comparison of some of the leading molecular imaging techniques is given in Table C-1.

A protocol published in 2012 uses conventional keV ToF-SIMS imaging to determine whether a fingerprint was made before or after an ink line has been drawn. The images in Fig. C-2 show the differences between the two cases using mass peaks associated with the ink and the fingerprint. Figure C-2 A shows that when a fingerprint is deposited on top of an existing ink line, the ink molecules (M:358.2 and 372.2) corresponding to the dyes are masked in the areas where the fingerprint ridges are found (determined from M:88.1 and 551.5).

TABLE C-1. COMPARISON OF SOME OF THE LEADING MOLECULAR IMAGING TECHNIQUES*

Information	MALDI MS	SIMS	Ambient MS	NanoSIMS	MeV SIMS	LA-ICP-MS
Spatial resolution	10 µm	> 200 nm for organics	> 50 µm. Sub-micron in development.	50 nm	1 µm	> 100 µm
Size molecules detected	Up to ~ 150 kDa (large proteins)	Up to ~ 2 kDa (small peptides)	Up to ~ 50 kDa (medium proteins)	elemental	Up to ~ 10 kDa (large peptides)	elemental
3D ability	To be developed	Yes (5 nm depth resolution)	Potential to be developed	Yes	Potential to be developed	Some
Ambient and real time	Some (AP-MALDI)	×	✓	×	✓	×
Portable	Benchtop available	×	✓	×	×	×
Quantitative	With internal standards but difficult	Relative quantification	With internal standards	Can be with isotopic labelling	Unknown	✓

* Spoto, G. and Grasso, G., Spatially resolved mass spectrometry in the study of art and archaeological objects, Trends in Analytical Chemistry, 2011, 30, 856–863.

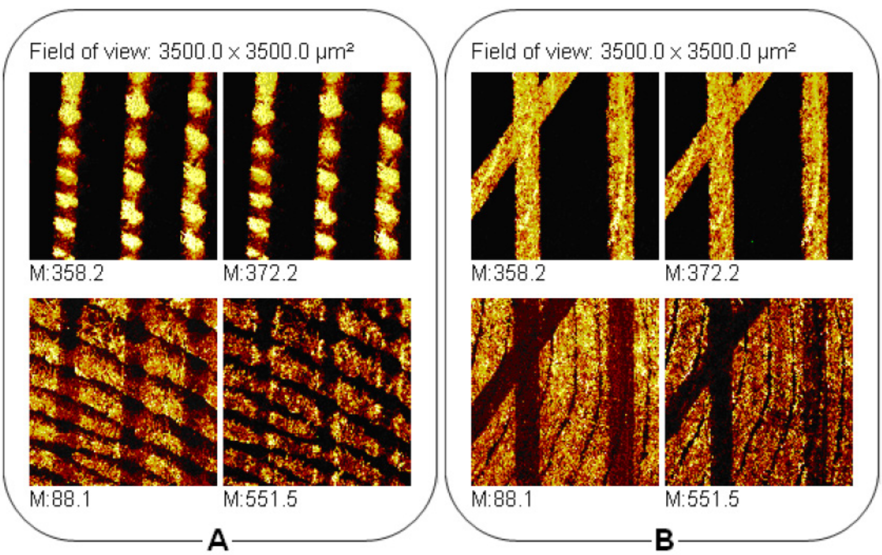

FIG. C-2. Positive ion images by keV ToF-SIMS of a fingerprint deposited (A) after ink and (B) before ink on a paper substrate. N.J. Bright et al., Analytical Chemistry, 84(9), 4083–4087, (2012).

Figure C-2 B shows that when an ink line is drawn across a fingerprint already deposited on paper, ions characteristic of the ink molecules (M:358.2 and 372.2) then mask and prevent the detection of those that are diagnostic of the fingerprint molecules (determined from M:88.1 and 551.5).

C.2. Research reactors

Research reactors comprise a wide range of different reactor types that are generally not used for power generation. The primary use of research reactors is to provide a neutron source for research and various applications, including education and training. They are small in comparison with power reactors, whose primary function is to produce electricity. Research reactor power ratings are designated in megawatts and their output can range from zero (e.g. critical assembly) up to 200 MW(th), as compared with 3000 MW(th) (i.e. 1000 MW(e)) for a typical large power reactor.

As of January 2013, there were 247 operational research reactor facilities in the world. In addition, there were 15 research reactors in temporary shutdown mode, and 150 in long term shut down. Of the operating reactors, 49 are high capacity, operating at high power levels and offering a higher neutron flux. An additional 304 research reactors have been decommissioned. Construction is on-going in a further four, of which two are in France (Jules Horowitz Reactor and the RES reactor), one in Jordan (sub-critical facility), and the Russian Federation (PIK reactor).[24] Finally, six research reactor projects were formally planned, in Argentina (RA-10), Belgium (MYRRHA), Brazil (RMB), Jordan (JRTR), the Netherlands (PALLAS) and the Russian Federation (MBIR), respectively. Five projects were cancelled prior to 2012. The distribution of age, power levels and utilization of operational research reactors are shown in Figs C-3 and C-5 and Table C-2, respectively.

Fifteen Member States are considering building or are planning new research reactors. Azerbaijan, Lebanon, Saudi Arabia, Sudan and Tunisia are in the early stages of planning to build a research reactor. In Jordan, construction has begun on a 5 MW multipurpose research reactor, while in Vietnam there are plans to build a new research reactor as part of an overarching commercial contract for a nuclear power plant. Countries with existing nuclear power programmes, such as Argentina, Brazil, France, India, the Republic of Korea, the Netherlands, the

[24] According to the IAEA's Research Reactor Database (http://nucleus.iaea.org/RRDB/), which contains records of current and formerly operated research reactors.

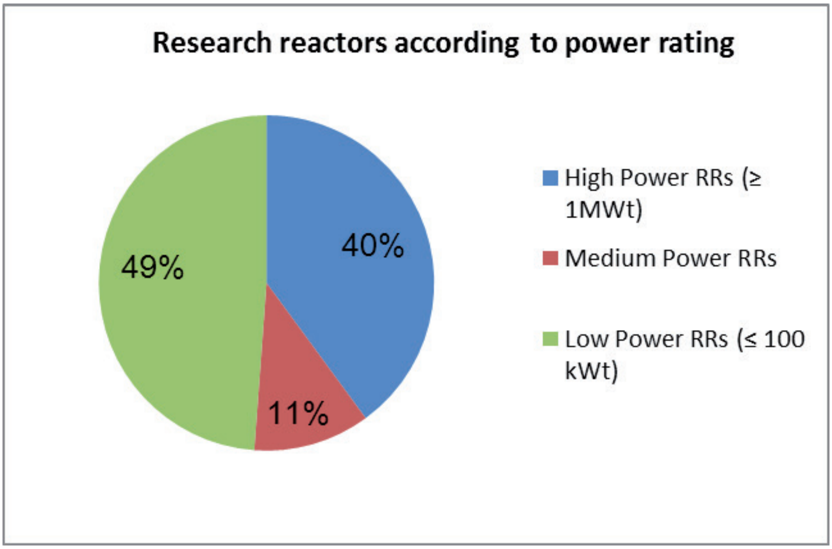

FIG. C-3. Power rating breakdown of operable research reactors (source: IAEA Research Reactor Database) as of August 2012.

Russian Federation and South Africa, are also building or planning new research reactors for specific experimental and commercial purposes.[25]

As older research reactors are decommissioned and replaced by fewer, multipurpose reactors, 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 2012, existing research reactor regional networks or coalitions, facilitated by the IAEA,[26] helped foster this cooperation and assisted research reactors in expanding their stakeholder base.

A new IAEA service, the Operation and Maintenance Assessments for Research Reactors (OMARR) service, was launched in 2012 to conduct comprehensive operation and maintenance peer reviews of research reactor facilities; verify compliance with existing plant procedures; suggest areas of improvement; and facilitate mutual transfer of knowledge and experience between mission experts and reactor personnel. The first OMARR mission,

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[25] A recent IAEA publication Specific Considerations and Milestones for a Research Reactor Project (IAEA Nuclear Energy Series No. NP-T-5.1, 2012) helps Member States in this area.

[26] 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.

TABLE C-2. THE COMMON APPLICATIONS OF RESEARCH REACTORS AROUND THE WORLD (IAEA-TECDOC-1234)

Type of Application	Number of research reactors involved[a]	Member States hosting utilized facilities
Isotope production	92	45
Neutron scattering	50	33
Neutron radiography	71	40
Material irradiation	70	28
Transmutation (gemstones)	20	11
Transmutation (doping of Si)	29	19
Teaching/training	165	53
Neutron activation analysis (NAA)	124	54
Geochronology	25	21
Boron neutron capture therapy (BNCT), including R&D	22	12
Other[b]	103	31

[a] Out of 252 RRs considered (229 operational, 15 temporary shutdown, 4 under construction and 4 planned; August 2012).

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

preceded by a pre-mission meeting that was held in June 2012, was completed in December 2012 at the reactor of the National Institute of Standards and Testing's Center for Neutron Research in the USA. A pre-mission meeting was also held in October 2012 for an OMARR mission to the TRIGA reactor at the University of Pavia in Italy. The main mission is expected to take place in 2013.

FIG. C-4. In 2012, the China Advanced Research Reactor achieved its nominal power of 60 MW operated in total for ~70 hours cumulative. As a result, 5 neutron beam instruments have been commissioned by obtaining the first neutron scattering patterns of required quality.

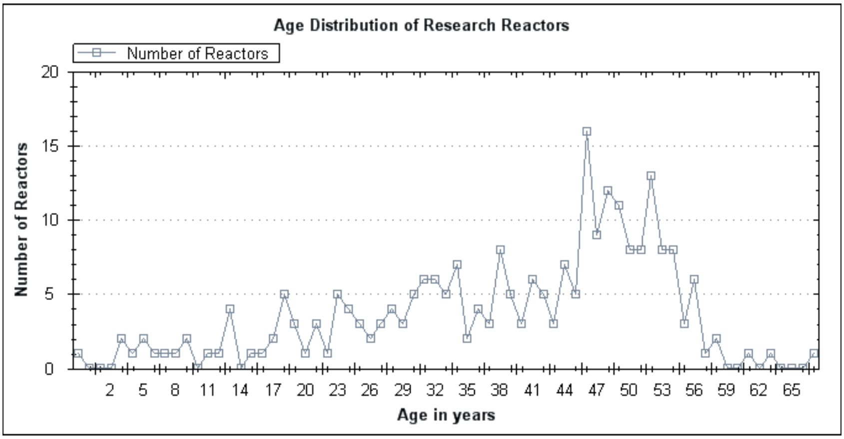

FIG. C-5. Age distribution of operable research reactors.

The GTRI continued throughout 2012 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 2012, 82 of these had been converted to LEU fuel or shut down before conversion. For example, in Mexico, the TRIGA MARK III research reactor was converted from HEU to LEU fuel, and its final HEU fuel was shipped back to the USA in March 2012. In Poland, in September 2012, the Maria research reactor was fully converted, using specially designed LEU fuel. In December 2012, GTRI announced the final removal of all HEU from Austria following the complete conversion of the Vienna TRIGA reactor (Fig. C-6) to LEU fuel. The safe repatriation of the Austrian fuel marks the final removal of all HEU TRIGA fuel from civilian commerce.

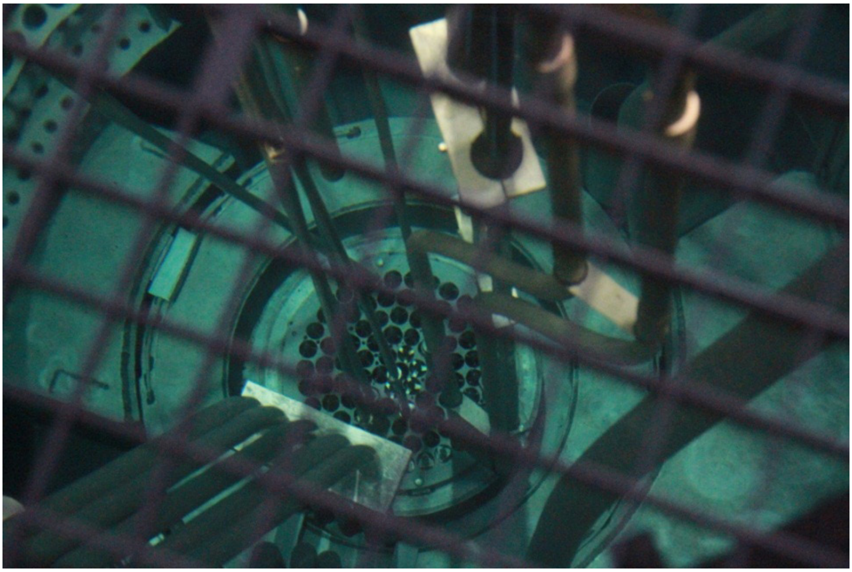

FIG. C-6. The core of Vienna Technical University's Triga Mark-II type research reactor with LEU fuel. The reactor was converted from HEU to LEU in 2012.

With IAEA support, several Member States returned HEU research reactor fuel to its country of origin. The Russian Research Reactor Fuel Return (RRRFR) programme continues to safely repatriate fresh and spent HEU fuel to the Russian Federation. In 2012, the IAEA assisted in the repatriation of nearly 110 kg of fresh HEU fuel from the Kharkov Institute of Physics and Technology, Ukraine, and of approximately 20 kg of HEU spent fuel from the Institute for Nuclear Research in Kiev after the conversion of its research reactor from HEU to LEU fuel. In August and September 2012, two more spent fuel shipment operations of nearly 100 kg of HEU were completed from Poland and Uzbekistan. One additional shipment to remove about 27 kg of fresh HEU was also successfully completed from Poland. China continued its efforts to convert its miniature neutron source reactors from HEU to LEU, and is planning on working with the Member States that have purchased such reactors in helping convert the reactors and repatriate the HEU fuel.

Conversion to LEU and repatriation of HEU fuel is often followed by significant infrastructure upgrades. For example, 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 following the repatriation of all HEU to the Russian Federation. The facility is planned to commence operation in 2014.

During 2012, the supply shortages of the past several years had finally abated and production levels returned to normal, although questions remain regarding mid to long term supply. The conversion of medical isotope production processes from HEU to LEU continued with a renewed focus during this period. Australia announced the expansion of its LEU molybdenum-99 production capability, to meet approximately 25% of global demand. To achieve this output, a new export scale nuclear medicine manufacturing plant will be built by 2016, as will a collocated Synroc waste treatment plant for the additional waste generated by the molybdenum-99 plant expansion.[27] South Africa continued its commercial production of molybdenum-99 made from LEU targets as well as the conversion of its processes to the exclusive use of LEU, while two major medical isotope producers (Belgium and the Netherlands) also started the implementation of plans to convert their commercial scale production processes from HEU to LEU. Finally, Indonesia became a fully LEU based small scale producer at the end of 2011.

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 the development and qualification of uranium–molybdenum fuels was made prior to 2012, further efforts and testing, particularly in the context of 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, very high density LEU fuels.

Following the conversion of relevant TRIGA reactors, global demand for TRIGA fuel decreased. During a 2010 research reactor fuel conference,[28] TRIGA International announced that a weak business case for fuel supply challenged their long term ability to supply fuel. Since then, the price of fuel has increased significantly, challenging the ongoing operation of several of the 38 operable TRIGA reactors worldwide.

In 2012, the IAEA continued its support to further the use of research reactors for education and training. These projects included finding ways to increase the number and types of training courses available and involving research reactors in basic scientific education.

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[27] Synroc is an Australian technology that uses hot isostatic pressing to reduce the volume of nuclear by-products by as much as 99% (compared to other methods such as cementation).

[28] The International Topical Meeting on Research Reactor Fuel Management (RRFM) 2010, organized by the European Nuclear Society (ENS) in cooperation with the IAEA, held in Marrakesh, Morocco, on 22–25 March 2010.

D. NEW TECHNOLOGIES TO IMPROVE FOOD SECURITY AND SAFETY

D.1. Developing strategies and technologies for preparedness and response to nuclear and radiological emergencies affecting food and agriculture

Many factors need to be taken into account in establishing a strategy for preparedness and response to potential nuclear or radiological emergencies that might affect food and agriculture. While a common approach is advantageous, any strategy must take into account local, site specific conditions in order to be effective.

Radionuclides were released into the environment during the Chernobyl and Fukushima Daiichi nuclear accidents. In Fukushima, high levels of radioactive caesium and iodine were detected in soil and plants, and a food monitoring programme generated data that resulted in the issuance of the first restrictions on the distribution of specific foods on 21 March 2011. The Fukushima Daiichi accident, like the Chernobyl accident, demonstrated clearly that it is critical that harmonized field and laboratory practices using consistent sampling protocols and analytical strategies for foodstuffs and soils are implemented as soon as possible after an event.

D.1.1. Emergency preparedness and response: the need for harmonized analytical procedures and sampling protocols

Following any event resulting in the release of radioisotopes into the environment, sampling strategies should be used to determine the radioisotopes of concern as well as the magnitude and spatial distribution of contamination. A standard approach based on appropriate baseline information should be used to avoid inaccurate comparisons of radionuclide concentrations. For example, when agricultural lands are contaminated, the soil sampling depth (topsoil versus crop rooting zone) that is selected needs to be the same.

The lack of harmonized protocols in field sampling and laboratory analytical practices can also produce inconsistent data, which makes sound decision making difficult. For example, the rinsing of radionuclides from the surface of leafy vegetables can influence the amount of radionuclides detected and the use of different laboratory procedures (rinsed or non-rinsed samples) could complicate the interpretation of data used for the implementation of food restrictions.

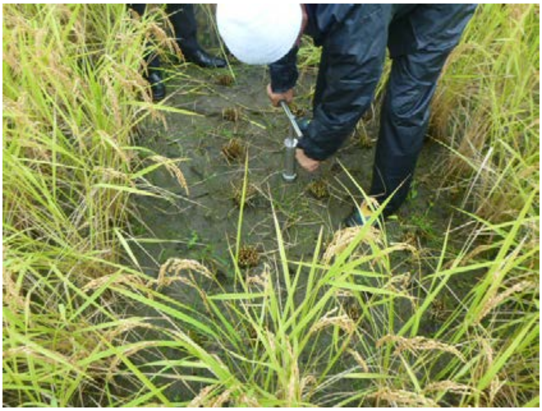

FIG. D-1. Soil sampling in affected rice fields, Courtesy of Ministry of Agriculture, Forestry and Fisheries, Japan.

It is therefore crucial that food and agriculture control authorities use harmonized protocols and procedures. These procedures should be designed to ensure that a statistically sound number of samples, with an appropriate temporal and spatial distribution, are taken for different soil and foodstuff types. Guidance that helps determine the importance of analytical uncertainty, the type of analytical equipment used, and the methodology used (e.g. analysis in the field or in the laboratory), including sampling locations (in the field, at collection points, during transport, at distribution centres, at retail outlets or at markets), should be in place.

FIG. D-2. Testing techniques for monitoring radionuclides in the field, Grabenegg, Austria (IAEA, 2012).

D.1.2. Handling and interpreting the sampling data

A large volume of food sampling data can present major logistical challenges. Descriptive metadata (data about information content) and the production and organization of relational databases are essential when large volumes of data are collected. This helps to maintain data quality, allows for the production of detailed maps and data outputs, and provides accurate information to governments, consumers and regulators.

An additional challenge in data management is the depth and extent of geographical resolution between datasets. For instance, it is essential that food samples and the soil samples associated with the production areas have a similar geospatial (georeferencing) resolution to allow for the overlaying and more accurate presentation of the data. In this regard, global positioning systems (GPSs) can add value to the data by providing locational information for the benefit of stakeholders worldwide. This information also helps to carry out additional sampling at the same sites, allowing for monitoring temporal changes in radionuclide concentrations in food and soil.

D.1.3. Mapping the data

Mapping is an important activity that can be facilitated through the use of ground, air and water based surveys for monitoring radionuclide deposition after major accidents, for example, when airborne and ground based surveys are combined to map the spatial extent of radionuclide fallout. This information, together with soil and food monitoring data, is required for determining affected areas, providing a clearer picture of the contamination situation, and for identifying technically and socioeconomically feasible remediation options for the restoration of agricultural production. These data also assist in the application of agricultural countermeasures aimed at the timely communication of sound advice, including restrictions on the distribution and consumption of specific agriculture, forestry and fisheries products.

Ground-based monitoring can also be effectively implemented using gamma ray detectors mounted on suitable vehicles or carried by personnel. This type of equipment should include GPS capabilities to record the sample locations, thereby allowing the rapid identification of critical spots of contamination and enabling timely and sound decision making. Mobile monitoring in the field can also make it easier to pinpoint areas that may require further detailed sampling and surveillance. Recent developments include the linking of georeferenced data with geospatial mapping technologies for the rapid dissemination of information for decision makers and the public.

D.1.4. Conclusions

Leadership by the responsible authorities during and in the aftermath of catastrophic disasters, including nuclear accidents, is essential. This includes acting upon lessons learned and developing strategies and technologies to improve future preparedness and response to nuclear and radiological emergencies.

It is necessary to develop field and laboratory practices for harmonized sampling protocols and analytical strategies (including soils, agricultural commodities and foodstuffs) and control programmes for monitoring commodities. The reporting and management of food and agriculture data also need to be improved. This is especially an issue when many countries are affected by an event and a coordinated approach is needed for data collection and management. Modern equipment and software will also help to provide timely and accurate data so that regulators can base their response decisions on the best information available.

In conclusion, the development and implementation of practical, timely, effective and harmonized response measures is needed in order to restore agricultural production and ensure food safety. The implementation of these measures would enhance accurate and appropriate data collection during the response to a future emergency event, enabling the application of scientifically based countermeasures and remediation strategies to address uncertainty and restore confidence in the food supply.

D.2. New applications of food irradiation technologies

The role of food irradiation in improving food quality, ensuring food safety and reducing the risk of food borne diseases has been known for many years, and its potential is clear. Food irradiation can play a key role in meeting these challenges by reducing food spoilage, losses and waste and by preventing the spread of insect pests of economic importance while providing access to lucrative export markets.

According to the Food and Agriculture Organization of the United Nations (FAO), approximately one third (1.3 billion tonnes) of all food produced for human consumption every year is lost or wasted. The World Health Organization also estimates that food borne and water borne diseases kill 2.2 million people annually — and over 1.9 million of them are children.[29] Reducing food losses and waste and improving food quality and safety through the safe application of food

[29] Food Safety — Report by the Secretariat to the Sixty-Third World Health Assembly (A63/11) 25 March 2010, http://apps.who.int/gb/ebwha/pdf_files/WHA63/A63_11-en.pdf

irradiation technologies could therefore have an immediate and significant impact on global food security. Exports and trade in irradiated food are growing as the technology is more widely accepted and supported by international standards.

D.2.1. Food irradiation technology

Food irradiation is one of the few technologies to address both food quality and safety because of its ability to control spoilage and food borne pathogenic microorganisms (by inactivating and destroying them) as well as harmful insect pests (by making them incapable of reproducing) without significantly affecting the sensory and wholesome attributes of foods. Foods that are treated by irradiation provide the same benefits as alternative processes, such as heat, refrigeration, freezing or chemical treatments, but without significantly raising food temperatures or leaving potentially harmful residues. Irradiation can also be used to protect packaged foods by preventing cross-contamination with microbiological hazards after treatment.

FIG. D-3. Researchers at the Center for the Application of Isotope and Radiation Technology of the National Nuclear Energy Agency, Jakarta, Indonesia, prepare irradiated ready-to-eat meals for people with compromised immune systems, increasing dietary variety and minimizing risks of food-borne illness (IAEA, 2012).

Food irradiation involves exposing food to ionizing radiation under controlled conditions. Gamma rays, e-beams and X rays can be used for food applications under the internationally recognized standards of the Joint FAO/WHO Codex Alimentarius Commission and the International Plant Protection Convention. The various types of ionizing radiation have different properties and therefore present different technological benefits and disadvantages, but in general terms, a given dose of gamma, e-beam or X ray radiation produces the same effects of inactivating pathogenic and spoilage organisms, delaying ripening, and preventing insects from reproducing.

Food irradiation technology has developed significantly since it was proposed in the early 1900s and since the technology to make powerful sources of radiation was developed in the 1950s, and now includes new applications of ionizing radiation and different treatment techniques, for example in combination with cold or modified atmospheres.

Currently, food irradiation is carried out mainly in the Asia and the Pacific region and in the Americas, but globally, there are not enough irradiation facilities that treat food. Ionizing radiation is mostly used to sterilize medical devices and pharmaceuticals, to preserve artefacts, to process cosmetics and packaging materials and to improve the materials of consumer and manufactured goods. Most facilities are multipurpose and treat a wide range of products, and although food may be a small part of their throughput, few are designed to deliver efficiently the relatively low doses (0.1 to 10 kGy) that are used to treat food.

At present, most irradiated food is treated using gamma radiation. For example, of the approximately 170 food irradiation facilities in China, more than 95% use gamma radiation. The situation is similar in the case of facilities that irradiate food for European Union countries, where 26 facilities use gamma and 6 use e-beam radiation. However, the use of e-beams is increasing worldwide, and there is growing interest in using e-beams and X rays to treat foods both in research laboratories and at large scale commercial facilities.

D.2.2. Radiation sources

Radioisotope irradiation facilities use cobalt-60 or caesium-137 radioisotopes to provide gamma rays. Cobalt-60 is used in commercial facilities and in most research scale irradiators because of its higher gamma ray energies and its inherent stability as a metal, but some research irradiators use caesium-137, which has a longer half-life. One disadvantage of gamma radiation is that it cannot be 'switched off' and thus the facility must be operated continuously to make full economic use of the radioactive material (see Table D-1). Additionally, radioactive decay means that the duration of time that food is exposed to ionizing radiation has to be increased by a few per cent each month and that the radioactive source has to be periodically augmented with additional quantities of the radioisotope to maintain acceptable processing efficiency. These facilities have to be designed to ensure safe containment of the powerful radioisotope source but are relatively easy to operate.

Machine source facilities, i.e. those that produce e-beams or X rays, use electricity to produce ionizing radiation and therefore one of their advantages over radioisotope facilities is that they can be switched off when not needed. E-beams are produced by accelerating a stream of electrons by means of magnetic and electric fields. They deliver the dose at a high rate and in less than a second can impart a dose that a gamma irradiation facility would take several hours to deliver. However, e-beams do not penetrate food to as great a depth as gamma rays and are not suitable for treating large bulk consignments of food in one step. They are able to process smaller bulk packaged food items at a very rapid rate. E-beams are already being used for commercial applications in the medical, material modification and environmental industries, but few e-beam facilities are designed to efficiently treat food and research is needed to further develop e-beam technology for food applications.

X rays are generated when electrons are accelerated at a metallic target, for example tantalum, tungsten or gold, to generate a stream of X rays. Although a considerable amount of energy can be lost as heat, X ray irradiation is receiving increasing interest as it is more penetrating than e-beams and can therefore be used to irradiate large bulk packages without the need for a radioactive source. A facility in Hawaii uses X rays to irradiate fresh fruits and vegetables for export to mainland USA, and a large facility in Switzerland is now using this technique to sterilize medical devices. As new generation X ray machines with increased efficiency and improved engineering become available, it is likely that X ray irradiation will become more widespread in the future.

D.2.3. Trends

It is proving difficult to deliver radioisotope sources in many parts of the world because of the fear of terrorism and increasing logistical complexities associated with their transboundary shipment. One of the main reasons for the growing interest in e-beam and X ray technology is that they avoid the procurement, transport, storage, disposal and safeguard issues associated with radioisotope sources. Food irradiation also has an additional benefit in that machine based technologies do not involve radioactive material and its nuclear connotation, and so mitigate negative consumer perceptions. It is envisaged that e-beam and X ray technologies will therefore develop as an alternative food irradiation option.

D.2.4. Food exports and trade in irradiated foods

Few reliable data exist on the quantities of food irradiated worldwide, but a significant and increasing quantity of high value foods is known to be irradiated and traded annually. In most regions of the world there is a small but growing amount of food that is irradiated to comply with sanitary requirements. For

TABLE D-1. COMPARISON OF RADIOISTOPE AND MACHINE SOURCE IRRADIATORS

	Radioisotope irradiation	Machine source irradiation	
Application	Gamma radiation is shone on to food.	An e-beam is scanned across food.	X ray radiation is shone on to food.
Source	The radiation source is a radioactive isotope (commonly cobalt-60).	The radiation source is a machine that uses electricity.	
Penetration	Highly penetrating radiation (suitable for food pallets).	Limited penetration (suitable for food cartons).	Highly penetrating (suitable for food pallets).
Treatment time	Reasonable processing time (minutes/hours).	Very quick processing (seconds/minutes).	Intermediate processing (minutes/hours).
When not in use	Always on and must be stored in a safe position when not in use.	Can be switched off, therefore saves energy.	
Stage of development	Established technology, used in research and on a commercial scale.	More development needed for food applications. Used in research and on a commercial scale but mainly for non-food items.	A developing technology. More work is needed on food applications. Used in some research and a few commercial scale facilities.
Prevalence	Most irradiated food is treated at this type of facility.	Some food is treated by e-beam.	One commercial scale facility uses X rays to irradiate food.
Maintenance	Source strength diminishes with time and needs to be replenished.	Good electricity supply is required and the machine needs to be maintained.	

FIG. D-4. Preparing safe products for export using gamma irradiation technology, Hanoi, Vietnam (Photograph courtesy of C. Blackburn, 2012).

example, data published in 2012 indicate that over 9263 tonnes of food, mainly frog legs, poultry and spices, were irradiated in the European Union.

A significant and increasing proportion of food is being irradiated for phytosanitary reasons (for example, to eradicate fruit flies, mites and mealy bugs) and this relatively new commercial application is stimulating trade in irradiated foods. For example, fresh fruits and vegetables are irradiated at low doses (less than 1 kGy) for export to the USA following the decision of the Animal and Plant Health Inspection Service (APHIS) to allow irradiation as a ‘generic’ quarantine treatment for insect pests, excluding moths in certain life stages. APHIS is also allowing mangoes from Pakistan to be irradiated on arrival in the USA, and new food irradiation capacity is being created in Mexico with the US market in mind. Recent regulatory developments in the USA have also expanded the approval of gamma and e-beam facilities for the treatment of imported fresh produce at the point of import. Entrepreneurs are moving to utilize these approvals, stimulating interest in countries that would not otherwise have the capacity to irradiate food. It is likely that trade in irradiated fresh fruits and vegetables will continue to grow rapidly.

Several countries trade in irradiated fresh produce, including Australia, India, Mexico, New Zealand, Thailand, the USA and Vietnam. This is driving a growing trend of interregional harmonization of national approaches and strategies related to the commercialization of food irradiation through the control of insect pests of quarantine importance in fresh produce. This trend is supported by the international standards for phytosanitary measures of the International Plant Protection Convention, including standards developed through IAEA research initiatives such as guidelines for the use of irradiation as a phytosanitary measure and for phytosanitary treatments for regulated pests; the latter includes 14 internationally agreed irradiation phytosanitary treatments developed through IAEA coordinated research projects.

D.2.5. Conclusions

Increasing urbanization, population growth and climate change are raising concerns over the availability and affordability of safe, wholesome and high quality food. Conventional methods to minimize post-harvest food losses, including the use of fumigation and other chemical treatments, are increasingly coming under scrutiny in view of potentially hazardous consequences for the public and the environment, including certain chemical treatments that are restricted under provisions of the Montreal Protocol on Substances that Deplete the Ozone Layer. There is a need for the increased use of food irradiation, especially e-beam and X ray irradiation technologies if food availability and affordability is to improve substantially in the coming years. These technologies can provide an effective and safe treatment for ensuring food quality and reducing post-harvest losses worldwide.

Future advances are likely to include research to further develop food irradiation capacity using e-beam and X ray irradiation technologies. These new technologies will be important for regulators, policy makers, researchers and food industries in developing initiatives and policies for increasing trade in irradiated foods.

Irradiation also provides a post-harvest treatment that can ensure exports meet hygiene and quarantine requirements, thereby securing access to export markets and foreign exchange and thus helping to generate income that can directly benefit food producers who would not otherwise be able to take advantage of international trade opportunities.

E. NEW DEVELOPMENTS IN COMBATING CANCER WITH NUCLEAR TECHNOLOGIES

E.1. Recent advances in cancer radiotherapy

Radiotherapy effectively treats cancer by delivering an accurate dose to a tumour with minimal damage to normal surrounding tissues. Recent advances in photon radiotherapy offer potentially substantial advantages over conventional radiotherapy. These advances include techniques such as intensity modulated radiotherapy (IMRT), image guided radiotherapy (IGRT), stereotactic radiotherapy (SRT), stereotactic radiosurgery, stereotactic body radiotherapy (SBRT), robotic radiotherapy, helical tomotherapy, volumetric modulated arc therapy (VMAT) and respiratory gated radiotherapy. These technologies were briefly introduced in Nuclear Technology Review 2012.[30]

E.1.1. Issues concerning the introduction of these technologies

Some of the above technologies allow the delivery of previously unimaginable doses of radiation precisely and non-invasively to a discretely defined tumour volume. They have the potential advantages of improved dose distribution, reduced toxicity, quick treatment delivery and increased local control, all leading to increased chances of survival. However, the technologies are at different stages of clinical development and entry into widespread medical practice will require more supporting data from well designed randomized trials.[31] Evidence is emerging that IMRT makes it easier to spare normal tissues. For example, a recent review of the clinical evidence regarding IMRT found that IMRT maintains parotid gland saliva production and reduces acute and late xerostomia (dry mouth) during radiotherapy for locally advanced head and neck cancer.[32] It also reduces late rectal toxicity in prostate cancer patients, allowing safe dose escalation, and seems to reduce toxicity at several other tumour sites. In breast cancer, IMRT reduces acute toxicity and improves cosmesis compared with conventional tangential breast radiotherapy.

Basic 3-D conformal radiotherapy (3-D CRT) is now considered the standard technical approach and provides good quality treatment for the majority of patients at a reasonable cost per patient. Some of the new technologies, such as carbon-ion beam therapy, proton beam therapy, or SBRT, are appropriate

[30] IAEA NTR 2012

[31] Rosenblatt et al., Radiother. & Oncol., 2012.

[32] Staffurth, J. Clinical Oncol., 2010.

for specific types of cancer and specific clinical situations, but cannot replace traditional standard radiotherapy based on 3-D CRT photon therapy.

In order to select the most appropriate technology, it is necessary to have clear information about the technologies involved. Early trials involving some of the technologies have focused primarily on feasibility in clinical settings as a primary end point, whereas more recently the emphasis has been placed on outcomes. The new technologies also need to be assessed on parameters that incorporate quality of life measures, such as patient reported outcomes and quality adjusted years of life.[33]

FIG. E-1. A modern medical linear accelerator equipped for IGRT. This device enables increased radiotherapy precision by frequently imaging the target and/or healthy tissues just before treatment and acting on these images to adapt the radiation target.

E.1.2. Cost and efficacy of advanced radiotherapy techniques

Whether new and advanced radiotherapy technologies are used depends on their cost and efficacy. These technologies have higher capital and operating costs, involve more stringent quality assurance (QA) programmes and require appropriately qualified personnel. QA procedures that can meet the demands of advanced technologies are now being developed and will need to be implemented in conjunction with formal comparative clinical trials. The introduction of

[33] Vikram, Coleman and Deye, Oncol. 2009, Part I & Part II.

advanced technology options in radiation oncology also needs to be considered in the context of overall needs and priorities, where factors such as the availability of skilled radiotherapy professionals and funding and the maintainability of equipment are important. There is a need to train radiation oncologists, medical physicists, radiotherapy technologists, administrators and maintenance engineers. Each one of these professionals requires significant training not only in the new technology to be implemented but also quite frequently at the level of basic educational requirements to work in the field.

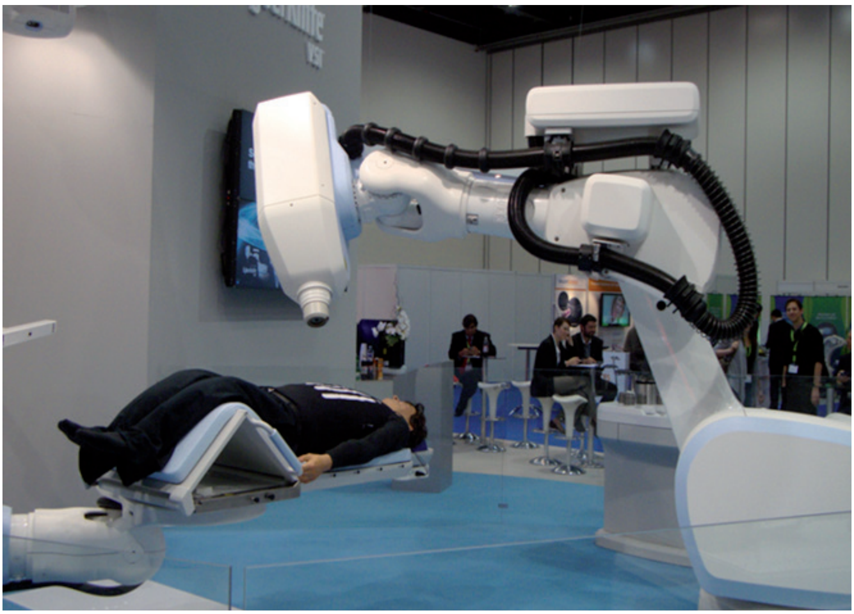

FIG. E-2. Robotic radiotherapy is a frameless robotic radiosurgery system. The two main elements of this device are the radiation produced from a small linear accelerator and a robotic arm which allows the energy to be directed at any part of the body from any direction.

E.1.3. Particle therapy for cancer treatment

Particle therapy refers to the use of ‘heavier’ subatomic particles in radiotherapy. Although the electron can be considered a particle, it is used routinely in clinical practice and has no extraordinary radiobiological properties. When the heavier particles (neutrons, protons, carbon ions) travel in tissue, they deposit more energy per unit track length (e.g. per cm). Therefore, they are more likely to damage DNA and kill cells. Photons or X ray based radiation deposit a high dose of radiation closer to the surface of the body. The absorbed dose decreases as the photon travels deeper into the tissue. Protons deposit little energy at the surface of the body. Additionally, protons release maximum energy (or produce dense ionization) near the end of their path in tissue. This release of energy is called a Bragg peak — in front of the Bragg peak, the radiation dose is low and, beyond the Bragg peak, the dose falls to zero over a very short distance.

The use of particle therapy for the treatment of cancer has a long history. It was developed in the early 1950s when the first treatments with a proton beam were implemented, followed by treatments with negative pi-mesons (charged subatomic particles) and neutron beams. The last two decades have seen an increased interest in and development of particle therapy, in particular proton beam therapy and carbon-ion beam therapy. There are now 40 particle therapy centres worldwide, including 6 carbon-ion beam centres. In addition, 25 facilities are being constructed and developed.[34]

Cost, however, remains an issue for such facilities. A cost analysis of external beam radiotherapy with carbon ions, protons and photons[35] showed that capital costs range from €23 million to €138 million (depending on the particular therapy combinations), with running costs per year ranging from €9 million to €36 million. In the case of proton facilities, newer compact commercial solutions have been developed. The cost of a single machine facility based on these new models is around €16 million, compared with a cost of €95 million for the traditional proton configuration.

A further issue regarding particle therapy is the extent to which the available scientific evidence supports the claim that this therapy is superior to standard photon beam therapy for the treatment of solid tumours.[36] Some experts working in particle beam facilities have claimed that there is no need or justification for clinical trials comparing, for example, protons versus photons, since the physical dose distribution and deposition of energy is clearly superior for protons.

However, other experts maintain that, just as in any other innovative modality of medical treatment, scientific evidence is needed to be able to justify a resource intensive modality as opposed to the standard treatment. The assumption that particle therapy is superior to photon therapy based on physical dose distribution alone is not, it is claimed, enough to justify replacing photon beam therapy with particle therapy.

More comprehensive data are therefore needed on the radiobiology, radiophysics and clinical outcomes of particle beam therapy.

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[34] Particle Therapy Cooperative Group (PTCG).

[35] Peeters et al., Radiother. & Oncol., 2010.

[36] Holtzscheiter et al., Radiother. & Oncol., 2012.

E.1.4. Brachytherapy

Brachytherapy is the administration of radiation therapy by placing radioactive sources adjacent to or in tumours or body cavities. In particular for gynaecological cancers, brachytherapy has gradually moved from the two dimensional approach to three dimensional planning based on cross-sectional imaging. In this modern approach, a computed tomography or magnetic resonance imaging scan is given to the patient after the brachytherapy applicators have been inserted. This makes it possible to see not only the applicators, but also the tumour itself, its extensions and the neighbouring organs that are at risk of radiation damage. The radiation dose is then prescribed not to a point, as in the past, but to a volume which encompasses not only the cancerous tumour and its extensions, but also the volumes at high risk of cancer cell contamination.[37]

Costs can vary significantly depending on the chosen technology. Some, such as 3-D brachytherapy, VMAT and SRT, can use some of the existing installed radiotherapy components for imaging or planning. Other technologies, such as those using carbon ions or protons need a completely new and dedicated facility.

To complement such facilities, there is a need for additional QA requirements including new equipment, additional staff, and time allocated to QA related activities.

The incorporation of advanced technology into treatment systems and its sustainability require additional investment in buildings and equipment, additional well trained human resources and expensive maintenance contracts for the sophisticated and delicate equipment involved.

E.2. Developments in radiopharmaceuticals for cancer imaging and therapy

Cancer is a disease that originates when the inner biochemical, molecular fabric of a cell is abnormally altered, thus escaping the usual control mechanisms that regulate tissue growth through a complex cellular signalling network. It is a complicated process, and although substantial progress has been made, there is still a lack of effective treatments for many cancers. This section highlights some recent developments in understanding cancer at atomic and molecular levels.

[37] Haie-Meder et al., Radiother. & Oncol. 2005.

E.2.1. Nanotechnology and nanomedicine

Nanotechnology is the manipulation of matter at the atomic and molecular levels to create new materials, devices and structures. At the molecular level, single atoms may have different properties compared with groups of the same atoms.

Size also matters in the fight against cancer because of different behavioural patterns at the atomic level. Unprecedented approaches based on the particular properties of certain nanostructures may help to fight cancer and this has led to the new field of nanomedicine, defined as the medical application of nanotechnology. It exploits the improved and often novel physical, chemical and biological properties of nanomaterials to enable the early detection and prevention of cancer, and to improve diagnosis, treatment and follow-up of the disease.

E.2.2. Properties of nanomaterials that might be beneficial for cancer therapy

Cytotoxic chemicals and radiolabelled compounds (radiopharmaceuticals) have historically been among the most effective tools for treating cancer. Chemotherapy and radionuclide therapies kill cancer cells, but they also kill healthy cells. Usually, chemotherapeutics and radiopharmaceuticals are small molecules that can easily diffuse and penetrate tissues, but making drugs that discriminate between cancer and normal cells remains very difficult. Nanomaterials, however, may offer a way to selectively target cancerous cells without damaging healthy tissues because of a previously unexploited weakness in tumour architecture. Tumours require the formation of new blood vessels to supply oxygen and other nutrients to sustain their rapid cell replication. As a result of the rapid growth of the new vessels, these are irregular and leaky with more and larger gaps in their walls than healthy blood vessels. The gap sizes range from a few hundred to a few thousand nanometres. In contrast, the pores in normal blood vessels are 2–6 nanometres wide. Nanoparticles in the range 10 to 300 nanometres are of an appropriate size to pass through the gaps of tumour blood vessels without significantly penetrating healthy tissues. In fact, nanoparticles selectively accumulate in tumour tissue anyway as a result of a purely physical phenomenon known as the enhanced permeability and retention (EPR) effect.

Nanoparticles have an ability to host a therapeutic substance inside their inner core which lends itself to applications in combination with the EPR effect. In this way, the nanoparticle’s surface layer will protect the encapsulated compound during its journey to the biological target. The internal content can be released to exert its therapeutic effect after reaching the target tissue. Nanoparticles can be designed to release their therapeutic payload in response to physical and chemical changes occurring at the target site such as, for example, when they encounter the acidic environment of the tumour core. Currently there are a substantial number of clinical trials involving nanotechnological reformulations of established chemotherapeutics to treat cancer.

E.2.3. Progress in pharmaceutical nanotechnology

Radionuclide therapy makes use of radiolabelled carriers — radiopharmaceuticals — that are designed to deliver a localized radiation source to the interior of the tumour area. Radiopharmaceuticals have two dosage components, a carrier and a trace amount of a radionuclide decaying through the emission of subnuclear particles. The therapeutic effect in tumour radionuclide therapy arises from alpha or beta particles emitted by the radionuclide and absorbed by the tumour. The ideal radiopharmaceutical should convey the radioactive nuclide selectively to the tumour tissue with no radiation reaching the normal tissues.

The investigation of novel tumour targeting radiopharmaceuticals is currently one of the most attractive fields of interest for both tumour imaging and treatment. In this context, the recent progress in pharmaceutical nanotechnology has been directed towards developing promising approaches based on the design of novel nanocarriers that are designed to improve the outcome of radiotherapy and the quality of diagnosis. A major challenge is how to firmly tether the radionuclide to its carrier molecule, and it appears that the nanotechnological approach may prove particularly advantageous. The encapsulation of a few radioactive atoms within the shell of a nanoparticle provides a simple approach to avoid spreading the radioactivity to healthy tissues and to deliver the therapeutic payload to the target cancer cells. Customized nanoscale systems can serve as targeted drug delivery vehicles capable of delivering large doses of radionuclides to malignant cells while sparing normal tissues and thus greatly reducing the side effects that usually accompany many current cancer therapies.

E.2.4. Targeting cancer cells

A further important characteristic of nanosystems is the extremely high surface-to-volume ratios that make the external surface (corona) of nanoparticles particularly suitable for coating with a large number of moieties (a part of a molecule) that can impart additional functional properties to the system. For example, nanoparticles carrying positively charged (cationic) coronas may easily penetrate most cell membranes as these have a net negative charge. Conversely, nanoparticles coated with neutral charge molecules will have a different distribution in the body and may have access to other specific targets.

Coating the nanoparticle's surface with functional molecules, such as antibodies or peptides that may take it through the interaction with receptors on the external membrane of cancerous cells, can also enhance tumour selectivity and specificity. Nanoparticle surfaces could also be coated with molecules that would help to evade recognition by the immune system, as well as with groups of molecules to help follow the route of the particle inside the body to ensure that it arrives at the intended place (Fig. E-3).

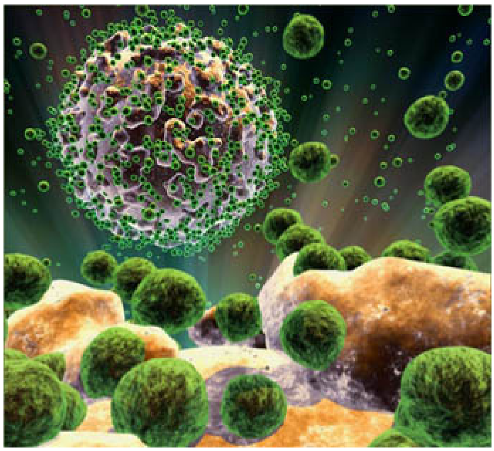

FIG. E-3. Pictorial representation of nano-sized globular particles (green), composed of a double-layered shell of lipids molecules, floating in the extracellular fluids and attacking cancerous cells to deliver their therapeutic payload.

It is estimated that during 2006 approximately 240 nanosized products entered the pharmaceutical research pipeline. Nanoliposomes, which are hollow bubbles enclosed by two layers of lipids, have often been the nanocarrier of choice for the delivery of therapeutic radionuclides contained in their internal cavity. A selection of nanotargeted cancer radiopharmaceuticals under clinical evaluation is given in Table E-1.

In addition to liposomes, researchers worldwide are exploring the possibility of using various natural and manufactured polymeric nanospheres as well as antibodies, RNA and DNA as nano-sized vehicles.

E.2.5. International research and development

A lot of research work is being carried out on the use of radiation technologies to synthesize nanostructured carriers for the targeted delivery of

TABLE E-1. SELECTED NANOTARGETED CANCER RADIOPHARMACEUTICALS

Nanocarriers	Radionuclides
Liposomes	Iodine-131, yttrium-90, rhenium-188, copper-67
Liposomes	Rhenium-186
Liposomes	Indium-111, rhenium-188
Liposomes	Indium-111, rhenium-188
Liposomes/immunoliposomes	Actinium-225
Immunoliposomes	Yttrium-90
Liposomes and dendrimers	Boron-10

therapeutics. Within the framework of an IAEA coordinated research project, Argentina, Brazil, China, Egypt, Hungary, India, Italy, the Republic of Korea, Malaysia, Poland, Serbia, Thailand, Turkey and the USA have elaborated methodologies aimed at nanoparticle and nanogel synthesis with precise control of the product structure, size and functionality. Several Member States have also worked on achieving compatibility with existing large scale irradiation facilities and procedures (Italy), as well as elaborating procedures for nanoparticles and nanogels based on proteins (Argentina, Brazil), natural polymers (Malaysia and Thailand), synthetic polymers (Egypt, Hungary, Italy, the Republic of Korea, Malaysia, Poland and Turkey) and inorganic compounds (China, France, India, the Republic of Korea and Serbia).

Procedures for hybrid nanostructures have also been developed where the surfaces of nanoparticles and nanogels are coated with functional polymers and biomolecules to increase their biocompatibility (France, Italy and Thailand). Nanoparticles based on chitosan (a substance produced from shrimp or other crustacean shells) were produced in Thailand by radiolysis. These and similar nanoparticles could be potential candidates for the immobilization of selected radionuclides.

Although several targeted nanocarriers for radiopharmaceuticals have been successfully applied to image and treat tumour models pre-clinically and clinically, there are numerous challenges still to be solved, such as the long term stability of nanocarriers, the scaling up of their production, and the possible toxicity and degradation products of nanocarriers.

E.2.6. Conclusions

Compared to conventional targeted radionuclide therapy, nanocarrier multifunctional targeting can deliver a higher payload of radionuclides, chemotherapeutics and/or imaging agents to tumour cells. This may play a crucial role in improving cancer treatment by selectively killing diseased cells while leaving healthy tissues unharmed, thus decreasing side effects and providing greater comfort for the patient. However, challenges still need to be addressed, including the long term stability and non-toxicity of the nanocarriers and the successful upgrading of the synthesis method to an industrial scale while maintaining the product specifications. These challenges will need to be addressed through extended cooperation between physicists, chemists, biologists, medical doctors, institutions, hospitals, industry and international organizations.

F. NUCLEAR TECHNOLOGIES TO ADDRESS THE IMPACTS OF CLIMATE CHANGE

F.1. Transforming agriculture to meet the challenges of climate change

The global population is estimated to increase to over nine billion by 2050, which will lead to a demand for increased agricultural production. As the supply of water and fertilizer is stretched and soil quality and fertility deteriorate, global food security is a significant challenge. In addition, climate change affects rainfall and weather events that may reduce water availability and have an impact on the environmental conditions necessary for agricultural production. Climate change affects agricultural activities, but agricultural activities also affect climate change. Agriculture is considered to be a significant cause of global climate change as it is responsible for more than 14% of GHG emissions.[38] Agriculture therefore must undergo a significant transformation to meet the challenges of adapting to climate change and mitigating its effect on land productivity and food security by identifying and using new technologies and practices that reduce the GHG footprint of agriculture.

F.1.1. Addressing climate change and food security challenges through climate smart agriculture

The transition to climate smart agriculture is being promoted by the FAO and its partners. It is defined as agriculture that sustainably increases productivity, resilience (adaptation), and reduces or removes GHGs (mitigation) while enhancing the achievement of national food security and development goals.

Climate smart agriculture addresses both adaptation to and mitigation of climate change. Adapting the agricultural sector is necessary in order to avoid losses and to create resilience. Adaptation practices include conservation agriculture, improved water use efficiency, water harvesting, crop diversification, animal breed selection and the use of integrated crop–livestock production systems. Mitigation includes measures that reduce GHG emissions from chemical fertilizer applications and animal manure while enhancing GHG removal from the atmosphere by plants for subsequent storage in soil organic matter.

[38] FAO, (2012). Mainstreaming climate-smart agriculture into a broader landscape approach. Background Paper for the Second Global Conference on Agriculture, Food Security and Climate Change. Hanoi, Vietnam, 3–7 September 2012.

In 2012, the High Level Panel of Experts on Food Security and Nutrition that supports the Committee on World Food Security reported the importance of developing strategies for climate resilient agriculture and food security. In this context, climate smart agriculture revitalizes food production and rural development, particularly in developing countries in an economically, socially and environmentally sustainable manner. Such low emission agriculture does not compromise food security since resources are used more efficiently and there is reduced energy consumption.

F.1.2. The role of nuclear techniques in climate smart agriculture

Information about the proportion of water taken up for use by plants (transpiration) and of water lost by soil evaporation is needed in order to improve water productivity in agriculture, which is essential — particularly in water scarce environments — to reduce overall water use. This information can be used to develop management practices to maximize the use of water and increase understanding of the sources of soil salinity. Measurement of the isotopic signatures of oxygen-18 and deuterium in irrigation water and the water present in soil, plant and the atmosphere around the crops can be used to separate evaporation and transpiration and to estimate the associated water loss from irrigated soils. This technique can be used to quantify water use by the plant and water loss through evaporation at different crop growth stages and across different irrigation systems and to improve the understanding of the origin of salinity in the soil. This is useful for developing new practices and technologies to improve irrigation, crop water productivity and soil and water salinity management.

FIG. F-1. Crop residues left on soil surface in a coffee plantation reduce soil evaporation, Vietnam.

FIG. F-2. Water harvested in farm ponds is an important source for irrigation in rainfed farming areas, Brazil.

Soil organic matter (SOM) is an important component of soil fertility and quality. Carbon and nitrogen are two essential components of SOM. Part of SOM decomposes in the presence of moisture and carbon dioxide (CO_2) is released to the atmosphere. The other part is stable and does not decompose and, as a result, CO_2 is not released to the atmosphere. The addition of crop residues and animal manures, as well as the introduction of legume crops and crop rotation increases SOM. The carbon and nitrogen isotopic signatures (carbon-13 and nitrogen-15) in soil and CO_2 and nitrous oxide (N_2O) gases released can be measured in situ using portable field instruments and used to quantify the sources of organic matter lost from agricultural soils. This information can be used to identify management practices that incorporate more carbon and nitrogen stable SOM and thus reduce CO_2 and N_2O emissions from soil.

Information on the water demands of crops is important for accurate irrigation scheduling, and to forecast crop yield under a changing climate. Estimating these demands requires data on area wide soil water content. This has been a challenge in the past as most soil water measurements are point based. This means that numerous measurements are required, which is costly and time consuming. Recent developments in the use of neutrons generated naturally from cosmic rays and soils complement point measurements to provide a reliable measurement of soil water content at the overall field level and thus integrate soil moisture data over a large area (up to 40 ha). The technology also provides information on soil water content to a depth of up to 70 cm and it can be used to evaluate water distribution uniformity and efficiency making it easier to schedule irrigation when and where it is required and thus to reduce overall water requirements.

Crop varieties need to be developed that yield more with fewer inputs and are better adapted to adverse environments caused by a changing climate. Mutation induction using nuclear techniques generates genetic variation and contributes to improved biodiversity. Mutation breeding is used to develop varieties that have higher productivity and greater yield stability in adverse environments, including climate variations that cause floods, droughts, high winds and extreme temperatures. Improved mutants contribute to reduced land use and to better, more environmentally friendly farming. One example is hardy barley mutant varieties, developed to withstand harsh weather conditions at 5000 m above sea level in Peru. These mutant varieties have improved food security for seven million Andean native people and improved their livelihoods. Also, salt tolerant rice mutant varieties have been introduced in the coastal areas of Bangladesh. These mutant varieties are able to thrive in saline soils and, as a result, new areas can be used for agricultural production.

The greatest step forward will be the development of accelerated breeding methods for desired mutant traits, which could shorten the breeding cycle from 10–15 years to 2–3 years, thus providing a rapid response to Member State needs for the development of new crop varieties with a range of traits, such as shorter growing periods and tolerance to water and salinity stresses, storms and extreme temperatures.

FIG. F-3. Hail tolerant barley in the highlands of Peru. These barley varieties carry a mutation that produces hanging heads and are thus protected from storm damage. This has allowed barley to be grown at unprecedented altitudes and has increased barley yields in Peru by a factor of 6.

Producing healthy animals which can survive on more marginal feed resources, while at the same time increasing energy utilization from their feed and mitigating the GHG emissions produced as a by-product, presents a major challenge. Metabolic and genetic analyses of the digestive systems of livestock are carried out to characterize or determine the ecology and diversity of methanogens to identify the microorganisms present and their role in the digestion of nutritive components. This permits the development of strategies that optimize the efficiency of the ruminal microorganisms and/or rumen based feed additives in increasing energy uptake and decreasing methane and CO_2 emissions. In addition, the use of genetic markers for the selection of semen donors for desired traits, such as adaptability to hot and humid environments, disease resistance and improved milk and meat production, will help boost the livestock industry in the next decades. In all these investigations, nuclear and nuclear related techniques are used either as tracers (isotopic labelling of nutritive components to trace their metabolic pathways) or as laboratory methods (radioimmunoassay, molecular based genetic analyses, etc.) for measuring targeted parameters.

F.1.3. Conclusions

Efficient climate smart agriculture requires information on factors and drivers that influence soil–water–crop–livestock interactions so that the agricultural system can be effectively adapted to climate change. It is critically important to monitor and evaluate different on-farm adaptation and mitigation strategies to promote best farm management practices in order to enhance resilience, food security and long term benefits. Isotopic and nuclear techniques provide new information to assist the continuous improvement of climate smart agriculture.

F.2. Nuclear techniques to study climate change and its impacts on the marine environment

It is very important that tools and strategies are developed to enable the marine environment and its resources to adapt to climate change, as well as to mitigate the impact of climate change on them. As emphasized in the UN Secretary General’s Oceans Compact and in the international discussions held during the United Nations Conference on Sustainable Development (Rio+20), reaching this objective will require enhanced international cooperation in marine scientific research, monitoring and observation, especially of the more vulnerable ecosystems.

FIG. F-4. Coastal resources are threatened by climate change; among them, coral reefs are important pools of biodiversity and habitats and a nursery for many marine species (photograph courtesy of Robert B. Dunbar).

Since the nineteenth century, the atmospheric concentration of CO_2 has increased from 280 parts per million (ppm) to 390 ppm in 2011. CO_2 is the primary GHG that regulates the global heat balance on earth. The ocean absorbs about one third of the total annual anthropogenic CO_2 emissions that result mainly from fossil fuel burning and changing land use.

The increase in atmospheric CO_2 is known to be a major contributor to climate change and related problems, such as global warming, sea level rise, ocean acidification, oxygen depletion and increases in the frequency and intensity of extreme weather events. In turn, climate change has various major direct and indirect effects on fish resources, coastal aquaculture, coral reefs and other coastal resources, as well as human habitation patterns in large low lying coastal cities. Alterations in the water cycle also cause changes in coastal erosion and in the distribution, transport and bioavailability of nutrients and pollutants that may result in eutrophication (the process by which water becomes too rich in nutrients, enhancing the growth and further decomposition of algae and plants which will consume more oxygen and ultimately lead to oxygen depletion in water) and contamination of seafood and aquaculture products.

Nuclear technologies are important in understanding some of the basic scientific questions about the impact of environmental conditions in the ocean on marine ecosystems and organisms.

Radionuclides and stable isotopes can be used to study numerous environmental parameters in historical climate studies such as temperature, rainfall, and the acidity of seawater. Glaciers, sediments, ice sheets and corals can be used as ‘storage systems’ or ‘recorders’ of the environmental conditions at the time of their formation. Radionuclides and stable isotopes can also be applied to better understand physiological processes such as calcification or bioaccumulation of chemicals and related responses of organisms to changing environmental conditions.

Nuclear and isotopic techniques have been used and developed at the IAEA Environment Laboratories to contribute to the global understanding of changes in the marine environment related to climate change, including ocean warming and ocean acidification.

F.2.1. The El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) phenomenon is a dramatic climatic event, which occurs every few years and has a great impact on the weather and on the economies of many countries in the Pacific region. It also has some effect on ice formation in the Antarctic. ENSO is coupled to variations in surface seawater temperature of the tropical eastern Pacific Ocean (the warming and cooling are known respectively as El Niño and La Niña) and in the air surface pressure in the tropical western Pacific. It also modifies oceanic circulation locally, which is one of the key processes that control the climate of our planet.

The extremes of these climate pattern oscillations cause severe weather conditions such as floods and droughts in many regions of the world and have a major impact on fisheries in many countries. Those countries dependent upon agriculture and fishing, particularly those bordering the Pacific Ocean, are most affected.

Studies of the ENSO phenomenon using both radionuclides and stable isotopes show that during El Niño events ocean temperatures in the tropics and subtropics shift, and are accompanied by variability in evaporation and isotopic fractionation, which are changes in the deuterium, carbon-13, carbon-14 and oxygen-18 isotopic compositions of seawater. These changes can be studied in sediments, corals, glaciers, cave water reservoirs or tree rings. These investigations help to explain the occurrence of ENSO phenomenon over a period going back several millennia.

F.2.2. The carbon cycle

The ocean is a major carbon sink and the trapping of increasing quantities of CO_2 is causing the ocean to become more acidic. 'Sinking particles' are the main mechanism by which carbon and contaminants are transported from the ocean surface to the sea floor. This includes atmospheric carbon, which is converted from CO_2 to biomass and sequestered to deep water via particle sinking. It is therefore essential to understand the mechanisms that control the fluxes of material from the ocean surface to the seafloor.

The natural radionuclide thorium-234 has been used increasingly to quantify particle fluxes and carbon export from the upper ocean in the open ocean and in coastal environments. Thorium-234 is a particle reactive isotope that is produced in seawater by radioactive decay of its dissolved parent uranium-238. The disequilibrium between uranium-238 and the measured total thorium-234 activity reflects the net rate of particle export from the ocean surface on timescales of days to weeks.

Several environmental processes related to climate change may alter the carbon cycle and carbon sequestration in the oceans. The increase in atmospheric CO_2 and the resulting increase in CO_2 in seawater are gradually affecting the acidity of the oceans. The increase in water acidity can affect several biological processes that result in particle formation and sedimentation through the water column (a notional column of water from the surface to the seabed). Changes in temperature affect the seasonal timing of the spring–summer water column stratification in many geographical areas of the world. This affects the dynamics of the export of particles and carbon, since water column stratification is a key physical process in the downward flux of particles. Warmer temperatures have already been shown to affect the extent and thickness of sea ice at high latitudes.

F.2.3. The impacts of ocean acidification

Modelling studies have clearly identified that polar and tropical regions are particularly vulnerable to the combined climate change effects of increasing temperature and ocean acidification. The IAEA is developing experimental studies to investigate ocean acidification effects to better predict their impacts on marine biodiversity.

Radioisotopes are valuable tools to investigate the responses of marine organisms to increasing temperature, the increasing partial pressure of carbon dioxide (pCO_2), and decreasing salinity and oxygen content. They have been used to provide evidence describing some of the biological effects expected to accompany global ocean change. Nuclear techniques are used to study several important biological processes, including calcification, biomineralization, metabolism and bioaccumulation of trace elements.

The beta emitting calcium-45 isotope is now commonly used to measure rates of calcification in many species, including reef building coral species. It gives a good estimation of the net calcification rate in calcareous structures. Biomineralization can be investigated through the incorporation of other major elements of calcareous structures, such as strontium-85.

Radioisotopes have been especially useful in investigating metabolic processes under contrasting environmental conditions. For example, the zinc metalloenzyme carbonic anhydrase is a catalyst in carbon uptake by marine organisms for photosynthesis, biomineralization processes, and systemic acid–base balance and is susceptible to ocean acidification or oxygen depletion in seawater. The radioisotope zinc-65 is used to assess the effect of elevated pCO_2 on organism metabolisms by studying its uptake kinetics. More generally, radioisotopes such as cobalt-57, cobalt-60, manganese-54 or selenium-75 are of interest given the metabolic importance of their corresponding stable isotopes. These trace elements have essential physiological functions and can be affected by warming, ocean acidification, hypoxia (oxygen depletion) or salinity change. Specific physiological processes such as ion regulation have been studied with highly sensitive techniques using radiotracers such as sodium-22 and chlorine-36.

F.2.4. Future effects

In the future, changes in the carbonate chemistry of oceans because of acidification, or in their salinity owing to increasing freshwater releases in coastal areas, are expected to alter the chemical speciation of trace elements and modify their bioavailability to marine organisms. In addition, temperature, hypercapnia (elevated CO_2), hypoxia (low O_2) and salinity change will hinder physiological functions such as ion regulation. Dissolved radiotracers can be used to investigate the bioaccumulation capacities under increasing pCO_2. Radioisotope analysis has provided valuable data for understanding mechanisms of toxicity in marine organisms and for risk assessment of contamination of seafood for human consumption. These techniques have a high sensitivity and resolution, and can be used to understand carbon driven effects on marine organisms and to reduce the uncertainty that exists concerning the biological outcomes of changing ocean chemistry. Reliable data and reduced uncertainty are essential for the production of accurate models of the effects on fisheries and estimates of the socioeconomic impacts of ocean acidification.

F.2.5. Stable isotopes in climate change studies

Stable isotopes are being used to study processes in the ocean that are highly relevant to climate change ocean acidification, and the global carbon cycle.

Fossil fuels display a unique ratio of the two stable isotopes of carbon (carbon-12 and carbon-13) and the combustion of these fuels leaves a distinctive isotopic signature in the atmosphere. The invasion of this anthropogenic signal in the ocean has been tracked by ocean measurements of carbon isotopes and, therefore, carbon-13 can be used as a fingerprint to investigate how the ocean acts as a sink for GHGs. Carbon-13 dissolved in seawater is also taken up by calcifying organisms, and so the carbon-13 signature in shells can be used as a palaeoclimatic dating tool. A reconstruction of seawater acidity is also being carried out based on the boron-11 isotopic composition of long lived massive corals. Alternative proxies, such as oxygen isotope records (oxygen-18/oxygen-16) locked up in the carbonate shells of marine microfossils, or in long lived corals, have been widely used to estimate past sea surface temperature, salinity, and circulation regimes, such as the intensity and frequency of past ENSO events as well as related glacial-interglacial changes. Long term changes in oxygen and hydrogen isotope ratios in precipitation also reflect variations in local climatic conditions such as in storm tracks, air mass trajectory, rain history and air temperature, all of which may be influenced strongly by changes in water mass circulation. Nitrogen isotopic ratios have also been used as a recorder of changes in the productivity and nutrient levels in the water column and origin of nitrogen compounds.

Other new techniques that use stable isotopes to track climate change include the measurement of the carbon and hydrogen stable isotope composition of specific lipid biomarkers that have been preserved in environmental archives, such as sediments. Specific lipid biomarkers, derived from once living organisms, can be traced back to their precursor compounds and their stable isotope composition reflects the environmental and climatic conditions at the time they were produced. They can therefore be used as indicators to reconstruct temperature, CO_2 levels, humidity, marine productivity and inputs from sediment derived from land erosion, as well as to assess basin wide vegetation and anthropogenic impacts on geological timescales.

F.2.6. Conclusions

Nuclear and isotopic techniques are unique tools that contribute to the understanding of chemical, biological and ecological modifications in the marine environment related to climate change.

The internal clock of natural radionuclides enables environmental recorders, in which isotopic proxies act for numerous environmental parameters, to be dated. The reconstruction of historical climate conditions in the carbonate shells of marine fossils, in long lived corals or in sediments can be used to help predict the behaviour of parameters such as temperature, rainfall and the acidity of seawater.

This knowledge is needed to study the ecological and socioeconomic impacts of future climate conditions on marine life and ecosystems, including fisheries and aquaculture, and to help societies in developing strategies to mitigate or adapt to these conditions, which will require constant and enhanced international cooperation in marine environment scientific research, monitoring and observation, especially of the more vulnerable ecosystems.

Annex I

PRELIMINARY LESSONS LEARNED FROM THE FUKUSHIMA DAIICHI ACCIDENT FOR ADVANCED NUCLEAR POWER PLANT TECHNOLOGY DEVELOPMENT

I–1. Introduction

The IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant,[1] which is based on the deliberations of an International Experts Meeting on the same topic in March 2012 in Vienna, emphasizes that the application of the defence in depth concept should be improved at two levels — the prevention of severe accidents, including through decay heat removal from the reactor core and spent fuel, and the protection of containment integrity. This paper reviews technological features — some already broadly deployed, others used only in new designs — that address both levels, and describes safety systems that can create options and extra time in an accident characterized, like the Fukushima Daiichi accident, by a loss of power, a loss of cooling water flowing through the core and a loss of the ultimate heat sink. These technologies offer ways in which designers can increase both the diversity of core and containment cooling systems and the ways those systems are powered, i.e. gravity, compressed gas, AC power, DC power and natural circulation.

Section I–2 summarizes passive core cooling systems to remove decay heat from the reactor core in an emergency. Section I–3 summarizes passive systems for cooling the containment and suppressing pressure. In fact, the highest levels of safety and reliability could result from carefully designed combinations of active and passive systems.

Section I–4 summarizes further technology options related to strengthening and venting containments, preventing hydrogen explosions, hardening instrumentation against radiation and cooling spent fuel.

I–2. Passive reactor core cooling systems

Passive core cooling systems can cool a reactor core without requiring AC electric power. They rely on combinations of gravity, natural circulation, DC power and compressed gas to transfer heat to either evaporating water pools

[1] http://www.iaea.org/newscenter/focus/actionplan/reports/spentfuelsafety2012.pdf

or to structures cooled by air or water convection. Six variations are summarized in this section.

I–2.1. Pressurized core flooding tanks (accumulators)

Pressurized core flooding tanks, or accumulators, are already used in some currently operating reactors as part of their emergency core cooling systems. They typically consist of large tanks about 75% full of cold borated water (Fig. I–1). The remaining volume is filled with pressurized nitrogen or an inert gas. The contents of the tank are isolated from the reactor by check valves that are held shut during normal operation by higher pressure in the reactor. In the event of a loss of coolant accident (LOCA), the reactor pressure will drop, opening the check valves and discharging the borated water into the reactor vessel. This is a one time discharge of cold water to buy time, of the order of minutes, prior to longer term emergency core cooling systems starting up. Accumulators do not provide continuing heat removal.

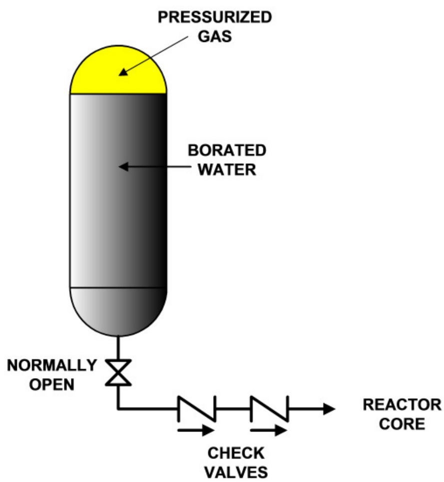

FIG. I–1. Pressurized core flooding tank (accumulator).

I–2.2. Elevated tank circulation loops (core make-up tanks)

Some new designs now under construction include elevated tank circulation loops (Fig. I–2). The tank is filled with cold borated water and normally isolated from the reactor by a valve in the discharge line at the bottom of the tank. The inflow line at the top of the tank is connected to the reactor cooling system. In an emergency, the bottom valve is opened to allow the cold borated water to flow into the loop. The cold borated water flows down into the core where it is heated, rises and flows back into the tank through the inflow line. Since the tank includes no heat exchangers or other means to remove heat, core make-up tanks also provide only short term discharges to buy time for other cooling systems to startup. They do not provide continuing heat removal.

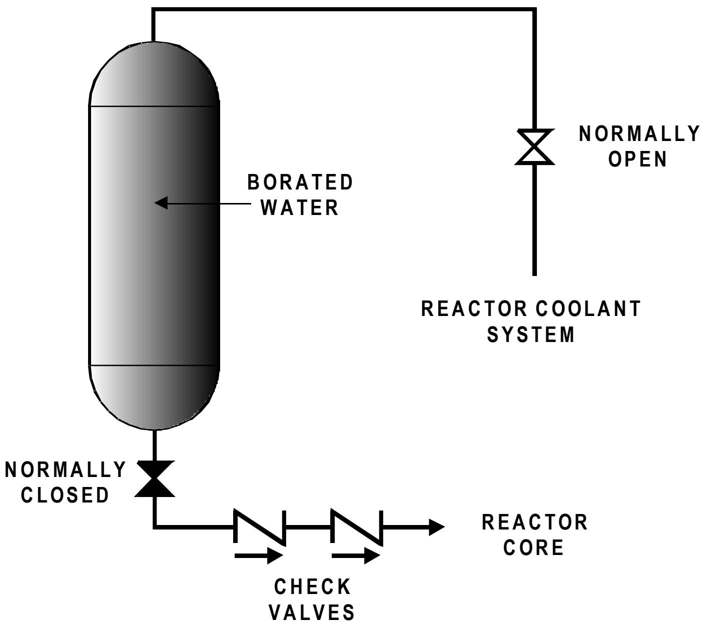

FIG. I–2. Elevated tank circulation loops (core make-up tanks).

I–2.3. Elevated gravity drain tanks

Elevated gravity drain tanks (Fig. I–3) are like the accumulators described in Section I–2.1, except they are driven by gravity rather than pressurized gas. They therefore are effective when the pressure in the reactor core is not greater than the weight of the water in the tank. They may be ineffective if the core is uncovered and generating high pressure steam. In some advanced designs, the volume of water in the tank is sufficiently large to flood the entire reactor cavity. Elevated gravity drain tanks also provide only a one time discharge of water to buy time.

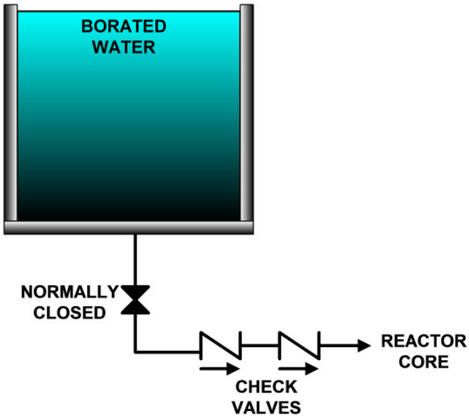

FIG. I–3. Elevated gravity drain tank.

I–2.4. Passively cooled steam generator natural circulation

Some advanced pressurized water reactor (PWR) designs incorporate an emergency passive, natural circulation cooling loop to remove heat from the steam generators either to a large water-filled cooling tank (Fig. I–4) or to the air through cooling towers (Fig. I–5). Both options could provide continuous rather than short term cooling during an emergency, although a cooling tank would require refilling as its contents evaporate, depending on the heat load, over a period ranging from less than a day to several days. Both options would only be effective if the emergency left the cooling loops that remove heat from the core to the steam generators undamaged.

I–2.5. Passive residual heat removal (PRHR) heat exchangers

PRHR heat exchangers are incorporated into several advanced PWR designs (Fig. I–6). They work in the same way as the passively cooled steam generator natural circulation loops described in Section I–2.4, except that they would remove heat directly from the reactor core, not the steam generators. They would thus provide continuous cooling during an emergency, with the caveat noted above that the cooling tank would require refilling as water evaporates, and would be effective even if the emergency had damaged the cooling loops that remove heat from the core to the steam generators.

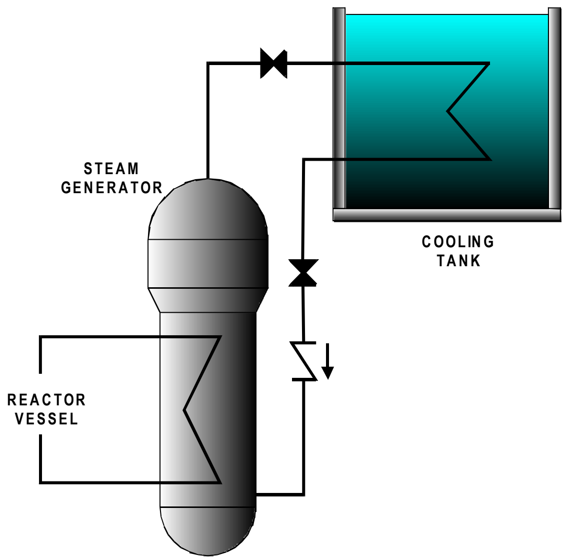

FIG. I–4. Core decay heat removal using a passively cooled steam generator (water cooled).

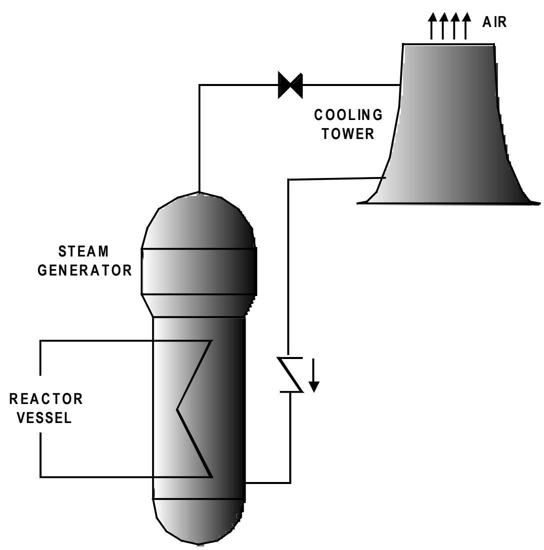

FIG. I–5. Core decay heat removal using a passively cooled steam generator (air-cooled).

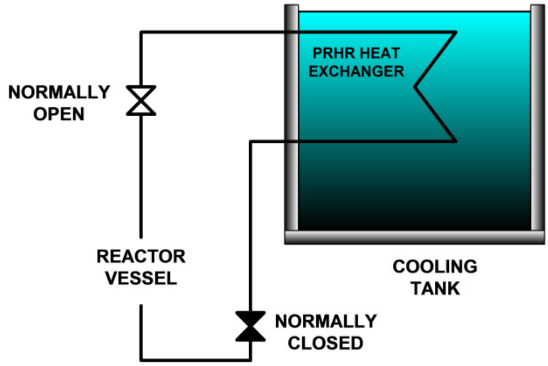

FIG. I–6. Core decay heat removal using a water cooled passive residual heat removal heat exchanger loop.

I–2.6. Passively cooled core isolation condensers (steam)

Passively cooled core isolation condensers (Fig. I–7) are included in early boiling water reactor (BWR) designs, including Unit 1 at the Fukushima Daiichi plant. The steam generated in the core is sent to isolation condenser (IC) heat exchangers in large water pools. The steam is condensed, and the condensate returns by gravity to the bottom of the reactor vessel to complete the loop. The system thus provides continuous, although limited, cooling to prevent the reactor from overpressurization. For Unit 1 at the Fukushima Daiichi plant, the IC failed to provide adequate cooling because the batteries needed for its operation were flooded by seawater.[2] The shutdown cooling system was unavailable because AC power had been lost.

I–3. Passive systems for containment cooling and pressure suppression

Passive systems can also be used to cool the containment and suppress pressure in the containment without requiring electric power. Three variations are summarized in this section.

I–3.1. Containment pressure suppression pools

Containment pressure suppression pools (Fig. I–8) have been used in various versions in BWRs for many years, including at the Fukushima Daiichi

[2] For more detail, refer to Ref. [3], p118.

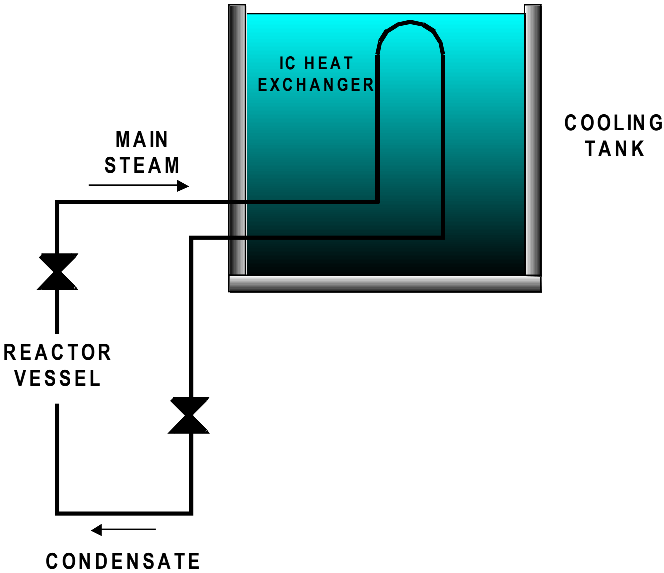

FIG. I–7. Isolation condenser cooling system.

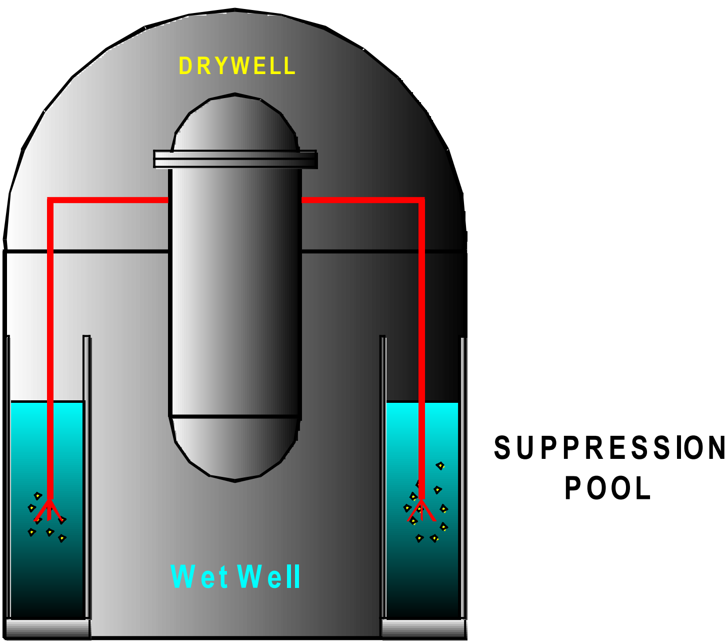

FIG. I–8. Containment pressure reduction following a LOCA using steam condensation in suppression pools.

plant. They work by forcing the steam collecting in the containment (also referred to as the drywell) through large vent lines submerged in water in suppression pools. The steam condenses to a much smaller volume thus suppressing pressure increases in the containment. Longer term heat removal to continue to suppress pressure increases requires active systems. During the Fukushima Daiichi Accident, the longer term, larger volume, shut down cooling system at Unit 1 and residual heat removal system at Units 2 and 3 failed because of the absence of AC power.

I–3.2. Containment passive heat removal / pressure suppression systems

This approach uses natural circulation cooling loops and an elevated pool as a heat sink. Figures I–9, I–10 and I–11 show three variations. The forces driving the natural circulation may be low in all variations, and careful system

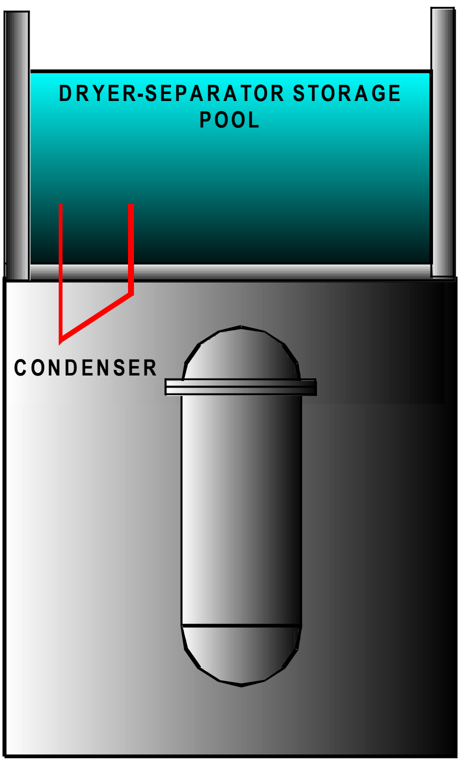

FIG. I–9. Containment pressure reduction and heat removal following a LOCA using steam condensation on condenser tubes.

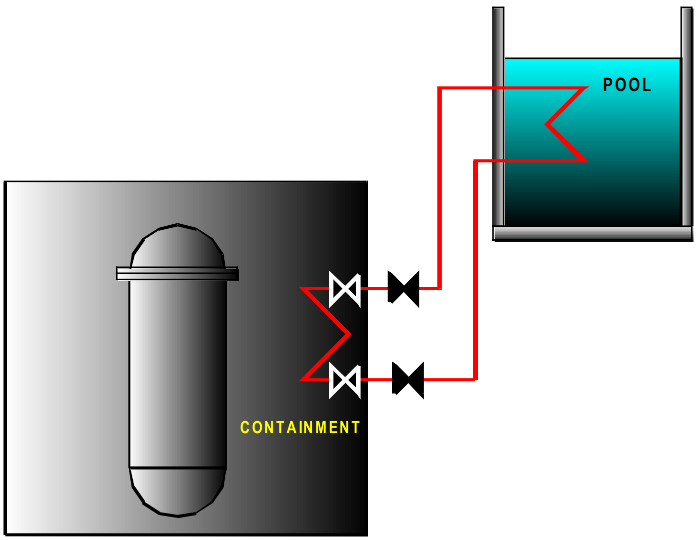

FIG. I–10. Containment pressure reduction and heat removal following a LOCA using an external natural circulation loop.

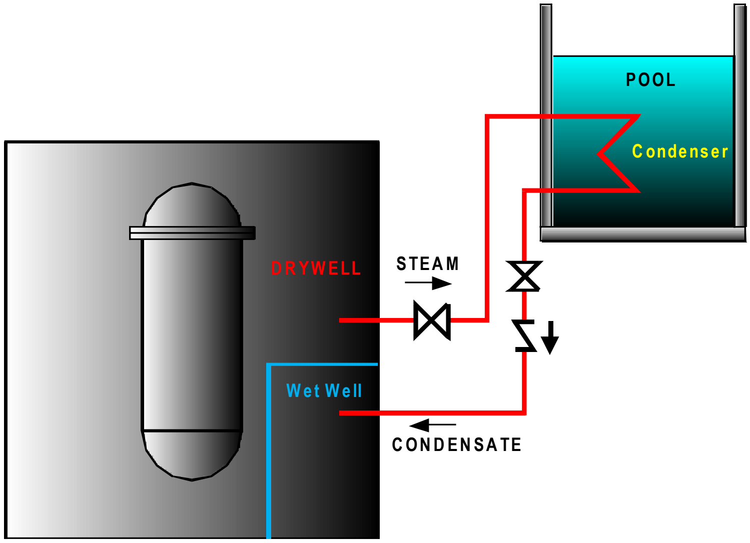

FIG. I–11. Containment pressure reduction and heat removal following a LOCA using an external steam condenser heat exchanger.

engineering is needed to ensure sufficient flow. Long term cooling would require replenishing the water that would evaporate from the elevated pool. Figure I–9 shows a condenser with inclined tubes connected with a pool on the top of the containment. Steam vented into the containment would condense on the tube surfaces, which would reduce the pressure and temperature in the containment. Cooling water would flow because of natural circulation driven by the heated water rising in the inclined tubes. This system has been implemented in a few newly operating reactors. Figure I–10 shows a closed loop in which the condenser in the containment is connected to an elevated heat exchanger in an external cooling pool, thereby establishing natural circulation in the cooling loop. Variations on this system were added to a number of reactors following the Three Mile Island accident in 1979 — in some cases as backfits and in others as features in newly built reactors. In the third variation (Fig. I–11), which is not yet incorporated in any operating reactor, the cooling loop takes steam directly from the containment, condenses it in tubes in the elevated pool which reduces the pressure and temperature in the containment, and returns the condensate to a separate zone in the containment referred to as the wet well.

I–3.3. Passive containment spray systems

In the design shown in Fig. I–12, following a LOCA, the steam in contact with the inside of the steel containment would condense. Heat would be transferred through the containment wall to the air outside the wall, which would rise as it is heated. It would be discharged through the top of the structure and replaced by cooler air continually entering at the bottom. A pool on top of the containment would provide a gravity driven spray of cold water to accelerate the cooling if DC power is available.[3] This system is included in some new plants currently under construction.

I–4. Further technology options

I–4.1. Containment design

The containment is the last barrier to prevent large radioactive releases from a severe accident. Technological improvements beyond the designs used in the Fukushima Daiichi plant include pre-stressed or reinforced single concrete containments with steel liners, cylindrical and spherical steel containments, and prestressed double containments with and without steel liners. These allow

[3] Power is needed because, to start the gravity flow, an actuator must explode to open the valve that holds back the elevated water supply. The signal to the exploder comes from a melting fuse located below the reactor vessel, and because the signal is sent automatically, without human action, the system is considered passive. Nonetheless, DC power is needed for the signal to be sent from the fuse to the exploder.

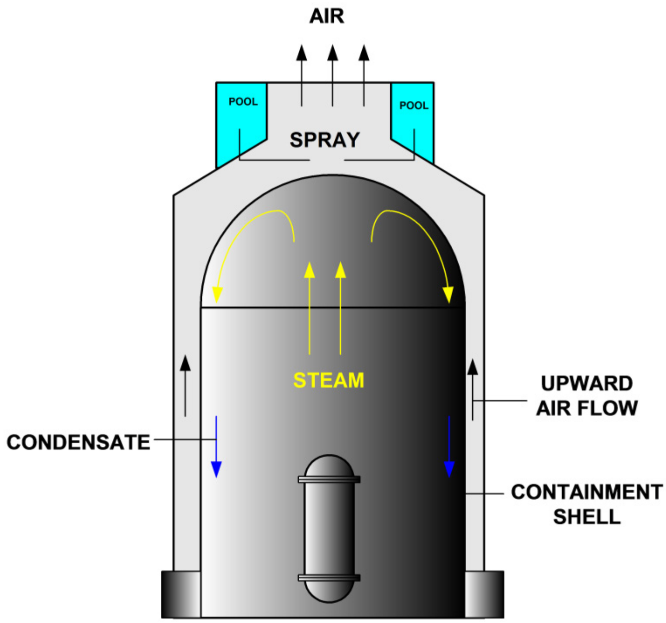

FIG. I–12. Containment pressure reduction and heat removal following a LOCA using a passive containment spray and natural draft air.

higher design pressures and lower leakage factors. Some designs also include core catchers to collect molten core material that melts through the reactor vessel and prevent it from escaping while also spreading it out to make it easier to cool. Each of these features is included in one or more of the advanced designs now in operation or under construction.

I–4.2. Prevention and mitigation of hydrogen explosions

During the Fukushima Daiichi accident, hydrogen explosions occurred in the reactor buildings of Units 1, 3 and 4. To prevent the accumulation of a dangerous amount of hydrogen in an accident, some more recent designs include hydrogen igniters and/or autocatalytic recombiners. Hydrogen igniters require power and are thus active, not passive, systems. Autocatalytic recombiners do not require power and are therefore passive.

I–4.3. Containment venting systems

To avoid dangerous pressure increases and hydrogen accumulations, it should be possible to vent the containment even under difficult conditions. During the Fukushima Daiichi accident, remote controls in the control room for venting were lost due to loss of power, and local manual venting was delayed due to high levels of radiation, and absence of electricity and compressed air necessary to operate valves.[4] Several currently operating nuclear power plants, however, have been, or are being, retrofitted with filtered containment venting systems. These create the option of venting to reduce the pressure and hydrogen levels in the containment without also releasing large amounts of fission products. Such systems could have avoided the delays during the Fukushima Daiichi accident but they could not have avoided the delays due to loss of electricity and compressed 'control air' for valve operation.

I–4.4. Instrumentation hardened against high radiation levels

During the Fukushima Daiichi accident, without power for instrumentation, operators could not fully monitor reactor conditions. It is essential to assure that instrumentation can survive the high temperatures, pressures, and radiation levels resulting from severe accidents, and that necessary power is available for essential instrumentation systems. The best improvement currently available is simply to add better shielding for vulnerable I&C systems. However, current research into radiation hardening has resulted in breakthrough developments of more robust cables, gauges, instrumentation, and electronic systems. Further research and development aims at the availability of hardened components for both new designs and backfits in existing power plants.

I–4.5. Spent fuel cooling

Although there was very limited damage to spent fuel during the Fukushima Daiichi accident, the accident did focus attention on possible scenarios that could have resulted in more severe damage. Because the pressures and temperatures associated with spent fuel storage are much less than those in the reactor, technological options for improving the diversity and reliability of spent fuel cooling and containment during an accident are relatively straightforward. Some advanced designs already incorporate emergency systems for cooling spent fuel and more robust pool structures with diverse approaches to monitoring and cooling. For future plants, spent fuel pools could be housed in containment-like structures.

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Annex II

NUCLEAR HYDROGEN PRODUCTION TECHNOLOGY

II–1. Introduction

Hydrogen is an environmentally friendly energy carrier that, unlike electricity, can be stored in large quantities. It can be converted into electricity in fuel cells, with only heat and water as by-products. It is also compatible with combustion turbines and reciprocating engines to produce power with near zero emission of pollutants. Therefore, hydrogen could play a major role in energy systems and serve all sectors of the economy, substituting for fossil fuels and helping to mitigate global warming.

Nuclear energy, in addition to its application for producing electricity, can also be used to generate hydrogen for direct use by energy consumers. Generating hydrogen using nuclear energy has important potential advantages over other processes. For example, it requires no fossil fuels, results in lower GHG emissions and other pollutants and can lend itself to large scale production. As a GHG free alternative, methods of using nuclear energy to produce hydrogen from water by electrolysis, thermochemical and hybrid processes are being explored. This paper briefly describes these three different processes.

II–2. Initial considerations regarding reactor types and processes

As long as it can provide electricity and process heat, any type of nuclear reactor can be used for the production of hydrogen. However, the reactor coolant and its maximum temperature are essential criteria for determining which reactor type is more appropriate for different production processes. Power size is also an important factor, as large reactors are more suitable for cogeneration of electricity and hydrogen production, whereas small sized plants are more suitable as single purpose plants (e.g. for hydrogen production only).

Specific considerations are more relevant for specific types of reactors. For instance, the cost of hydrogen generation would be less attractive for a small sized plant to be used for hydrogen production only, as could be the case when using light water reactors for hydrogen production. However, it is possible to make this process more economically interesting, e.g., using off-peak power or cogeneration to reduce or share costs. Small and medium power reactors based on high temperature gas reactors (HTGR) are also an attractive option. Future advanced nuclear power plants, such as the very high temperature reactors (VHTR) or the supercritical water cooled reactor (SCWR), could provide not only the electricity needed, but also deliver relatively high temperature process heat, providing high net power cycle efficiencies.

Steam reforming of natural gas[1] is dominant in today's refineries and the production of process heat by HTGR for the refining process could be a starting point towards a fossil free (and nuclear generated) hydrogen production. In comparison to a conventional steam reformer, the employment of a nuclear steam reformer requires certain changes, since the operational conditions of a nuclear reactor are not as flexible as those of a fossil fuelled furnace. Furthermore, safety requirements are much more stringent than for a fossil fuelled system. Therefore, the highest effectiveness in the use of nuclear process heat is required. A high hydrogen production rate is achieved if the process feedgas rate[2] and the conversion rate[3] are high.

II–3. Hydrogen generation by electrolysis

Electrolysis is the most straightforward process currently available to produce hydrogen directly from water (Fig. II–1). Although conventional low temperature electrolysis can be coupled with all currently operating reactors, it will not be economically competitive. At higher temperatures, various potential

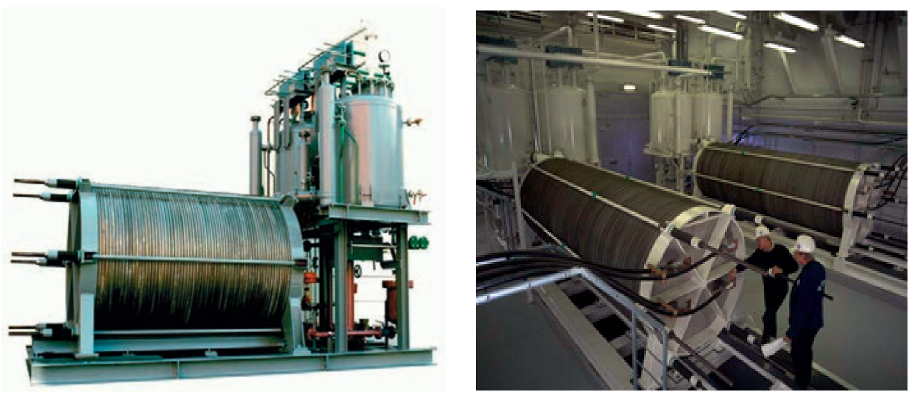

FIG. II–1. Standard low temperature alkaline electrolysis.

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[1] The steam reforming process is the catalytic decomposition of light hydrocarbons (e.g., methane, natural gas, naphtha) to react with superheated steam and resulting in a hydrogen rich gas mixture.

[2] The feedgas (e.g. natural gas/methane) rate depends on the amount of heat input into process gas and the temperature of process gas.

[3] The conversion (of natural gas into hydrogen) rate depends on the temperature and pressure of the process gas.

processes for hydrogen production, such as high temperature steam electrolysis and other thermochemical processes, have been identified. In this case, the use of high temperature reactors for hydrogen production presents a viable option since most of these processes have a higher efficiency than low temperature electrolysis. The types of electrolysis that are being considered for deployment on an industrial scale are, apart from the classical alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and high temperature steam electrolysis (HTSE) using oxygen conducting ceramics.

Electricity input required for electrolysis can be decreased by increasing the temperature range, as the total energy demand for electrolysis in the vapour phase is reduced by the heat of vaporization, which can be provided much more cheaply by thermal rather than electric energy. Indeed, in the high temperature range of 800–1000°C, electricity input could be about 35% lower than that of conventional electrolysis. In addition, the efficiency of electrical generation at these high temperatures is significantly better. The HTSE process is advantageous due to its high overall thermal to hydrogen efficiency when coupled with high efficiency power cycles.

As HTSE corresponds to the reverse process of a solid oxide fuel cell (SOFC)[4], respective devices could be operated in both modes. Therefore, HTSE development could benefit from ongoing R&D efforts in the SOFC area.

A high temperature electrolyser must be coupled to a heat and power source. At high temperatures, all reactions proceed very rapidly. The steam–hydrogen mixture exits from the stack and then passes through a separator to separate hydrogen from the residual steam. The feedgas stream to the HTSE cell contains a 10% fraction of hydrogen in order to maintain reducing conditions and avoid the oxidation of the nickel in the hydrogen electrode (Fig. II–2). HTSE cells can be operated at high current densities, which allow for large production capacities in comparatively small volumes. An electricity to hydrogen efficiency of about 90% could be achievable. However, the lifetime of the hydrogen electrode, which is limited by degradation, requires further improvement.

II–4. Hydrogen generation by thermochemical cycles

Besides high temperature electrolysis, another promising candidate to produce large amounts of hydrogen by high temperature water splitting is thermochemical process. The most straightforward method of water splitting would be one step direct thermal decomposition. However, this would require

[4] A solid oxide fuel cell is an electrochemical conversion device that produces electricity directly from oxidizing a fuel.

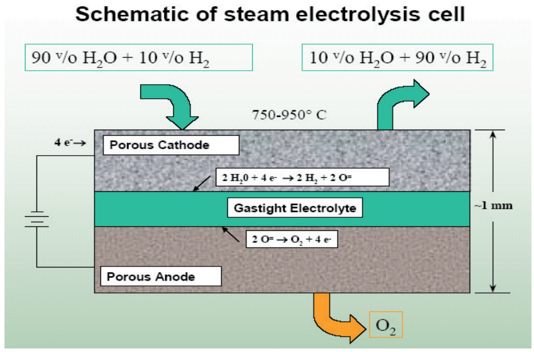

FIG. II–2. Schematic of a planar steam electrolysis cell.

temperatures of >2500 °C for reasonable quantities, which is industrially not feasible. Therefore, multistep processes are being considered.

A thermochemical cycle is a process consisting of a series of thermally driven chemical reactions where water is decomposed into hydrogen and oxygen at moderate temperatures. Supporting intermediate chemical compounds, which are regenerated and recycled internally and remain — ideally — completely in the system, are used in a sequence of chemical and physical processes. The only input to the cycle is water and high temperature heat. Therefore, these cycles are potentially more efficient than low temperature electrolysis and could significantly reduce production costs. Research on thermochemical cycles mainly focus on using solar or nuclear primary heat input.

Numerous thermochemical cycles have been proposed in the past and checked against factors such as: corrosion problems, cost analysis, heat transfer, material stability, maximum temperature, processing scheme, reaction kinetics, separation of substances, side reactions, thermodynamics, thermal efficiency and toxicity. Some have sufficiently progressed to be experimentally demonstrated and have already proven their scientific and practical feasibility. All cycles however, have design challenges and none has actually been implemented on a commercial scale.

A major challenge in thermochemical cycles is obtaining maximum yields while reducing the amount of excess reagents used to drive the reactions in the desired directions. Therefore, the optimization of heat flows is important for high energy conversion efficiency. One cycle under special consideration is the sulphur–iodine (S–I) process, also known as Ispra Mark 16 cycle, originally developed by the US company General Atomics and later taken up and modified by different institutions like the Japan Atomic Energy Agency (JAEA). This cycle basically consists of three chemical reactions (Fig. II–3). Of

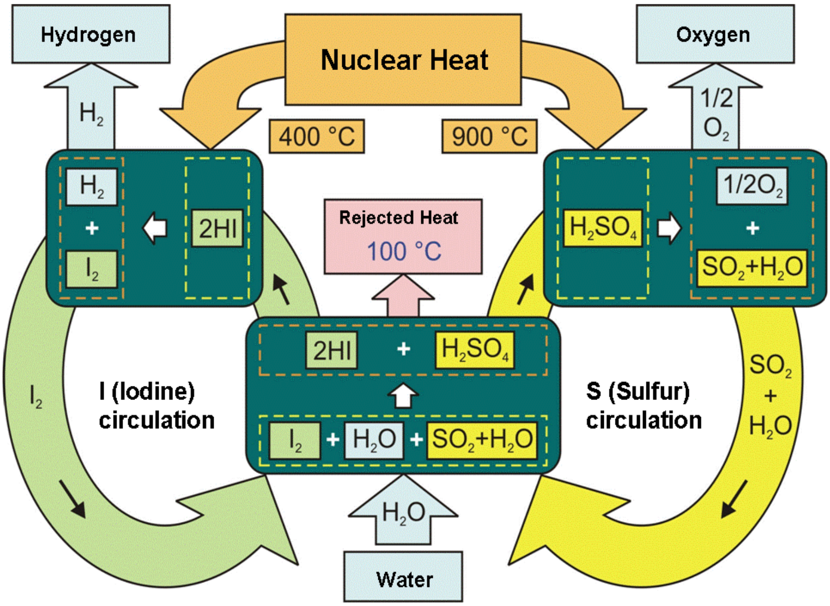

FIG. II–3. Schematic of sulphur–iodine thermochemical water splitting cycle.

all thermochemical cycles, the S–I cycle is the one with the highest efficiency quoted. The theoretical limit of efficiency for the total process is assessed to be 51%, assuming ideal reversible chemical reactions. Analytical studies anticipate efficiencies of 40–50%. As the result of a flow sheet analysis in 1982, General Atomics estimated the process thermal efficiency to be 47%. A schematic of the S–I cycle is shown in Fig. II–3.

In all studies that systematically examined thermochemical cycles, those of the sulphur family — S-I, hybrid[5] sulphur, sulphur–bromine hybrid — have been identified as the potentially most promising candidates, with higher efficiency rates and a lower degree of complexity (in terms of the number of reactions and separations). All three have in common the thermal decomposition of sulphuric acid at high temperatures (Fig. II–4).

II–5. Hydrogen generation by hybrid cycles

A hybrid cycle combines the benefits of thermochemical and electrolytic reactions. In this type of cycle, the low temperature reaction, which has a low thermodynamic efficiency and is therefore not favourable, is forced

[5] Hybrid cycles will be discussed later in this paper.

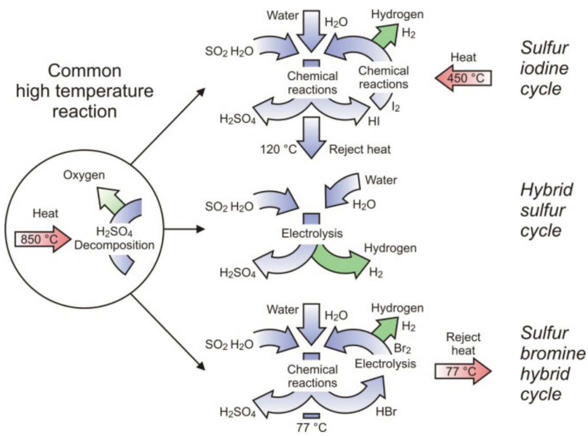

FIG. II–4. Thermochemical cycles of the sulphur family.

electrochemically. The hybrid sulphur (HyS) process, originally studied at the Los Alamos Scientific Laboratory and further developed by Westinghouse in 1973–83, is also known as the Ispra Mark 11 cycle. It is a variation of the S–I process which consists of only two reaction steps and where sulphur, apart from hydrogen and oxygen, is the only other element involved. A series of flash evaporators are used to separate oxygen from the liquid mixture resulting in almost pure oxygen. The rest of the mixture, consisting of mainly SO_2, sulphuric acid and water, is sent to the electro–chemical section. The mixture of SO_2 and water is reacted in an electrolytic cell at lower temperatures to produce H_2 and a sulphuric acid in an aqueous phase. Still, the net thermal energy requirement for the HyS process is significantly less than for conventional water electrolysis. SO_2 electrolysers require no more than 25% of the electricity that is needed in low temperature water electrolysis, i.e. ~0.29 V. Theoretically, this value could be decreased to 0.17V. Nevertheless, this would require that H_2SO_4 be decomposed at high temperatures in order to recycle the SO_2 for the completion of the cycle. The Westinghouse process (Fig. II–5) is simpler in design as the use of corrosive halides is not required. After the oxygen is removed from the system, the SO_2 and H_2O are combined with make-up H_2O[6] and routed to the electrolyser cell. The SO_2 is then electrochemically oxidized at the anode to form H_2SO_4, protons and electrons. The protons migrate through the electrolyte and produce H_2 gas at the cathode.

[6] Make-up H_2O is an additional amount of water added to the cycle to replenish/substitute the amount lost due to leakage and evaporation.

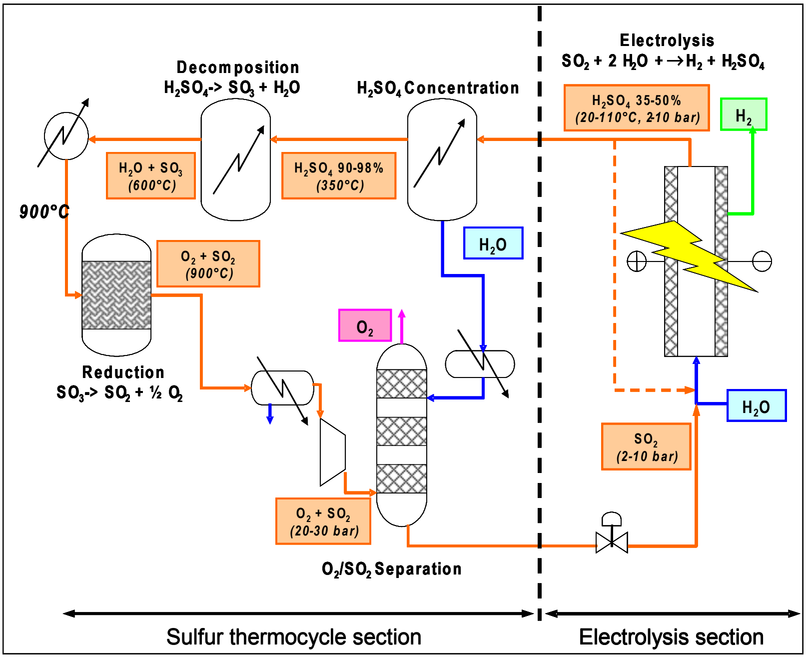

FIG. II–5. Schematic of the Westinghouse hybrid-sulphur cycle.

Developed as the Mark 13 cycle at the Joint Research Centre of the European Commission in Ispra, Italy (JRC Ispra), the sulphuric acid–bromine (S–Br) hybrid cycle uses bromine instead of iodine. The S–Br hybrid cycle uses elements in only liquid or gaseous form. The voltage required in the electrochemical step (0.8 V) is slightly higher than in the HyS cycle (0.6 V) using this method. In 1978 in a lab scale facility at the JRC Ispra, Italy, the cycle was successfully tested demonstrating a hydrogen production rate of 100 L/h over 150 h, with an efficiency of 37%. The system was also operated with a 1 kW solar heat source. However, reducing the energy requirement for the electrochemical step is currently the main area of focus.

Several alternative thermochemical cycles for hydrogen production, which operate at moderate temperatures in the range of 500–600ºC, have been investigated. Lower operating temperatures reduce the costs of materials and maintenance and can effectively use low grade waste heat, thereby improving cycle and power plant efficiencies. Additional advantages include ease of handling the chemical agents and reactions.

The US Nuclear Hydrogen Initiative (NHI) identified a number of chlorine based thermochemical cycles. The copper–chlorine (Cu–Cl) cycle, shown in Fig. II–6, can be operated at a maximum temperature of about 550°C. A hybrid

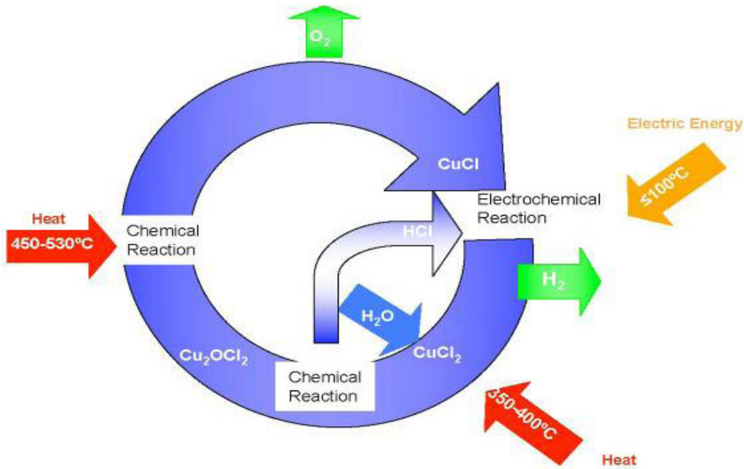

FIG. II–6. Schematic of the copper–chlorine thermochemical water splitting cycle.

cycle consisting of several thermal and one electrochemical reaction, the Cu–Cl cycle requires much lower operating temperatures than other cycles and can effectively use low grade waste heat. The steps involved in the cycle are shown in the schematic below. Potential efficiency could reach as high as 41%. The electric energy demand was assessed at 39% of the total energy required. The viability of all reactions and, in particular, the H_2 and O_2 generation, was demonstrated at the Argonne National Lab on a bench scale level. Nevertheless, side reactions and the completeness of the reactions are still being researched.

The iron–chlorine or 'Mark 9' cycle is one of the thermochemical cycles that have been extensively studied in the past. Some partial reactions are well known and technically proven. The endothermic reaction is the hydrogen producing step by hydrolysis of $FeCl_2$. The choice of proper material as well as the coupling to a process heat source still needs to be resolved. Also, separation of the solid and gaseous reaction products appears to be difficult, considering the melting point for $FeCl_2$ (950°C) and its high vapour pressure at such high temperatures.

Other hybrid cycles also appear feasible. The hybrid copper oxide copper sulphate thermochemical cycle, originally derived from the Westinghouse HyS cycle, appears to be feasible with the technology currently available. Another promising thermochemical process is the calcium–iron–bromine or UT-3 cycle, already developed at the University of Tokyo (UT) some decades ago. The process consists of four gas–solid reactions which include hydrolysis and bromination of calcium and iron compounds.

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