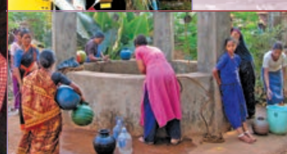
NUCLEAR TECHNOLOGY REVIEW

2012





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

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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
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CONTENTS

EXECUTIVE SUMMARY

In 2011, nuclear energy continued to play an important role in global electricity production despite the accident at the Fukushima Daiichi nuclear power plant (NPP). Total generating nuclear power capacity was slightly lower than in previous years due to the permanent shutdown of 13 reactors in 2011, including 8 in Germany and 4 in Japan in the wake of the accident. However, there were 7 new grid connections compared to 5 in 2010, 2 in 2009 and none in 2008. Significant growth in the use of nuclear energy worldwide is still anticipated — between 35% and 100% by 2030 — although the Agency projections for 2030 are 7–8% lower than projections made in 2010. The factors that have contributed to an increased interest in nuclear power did not change: an increasing global demand for energy, concerns about climate change, energy security and uncertainty about fossil fuel supplies. Most of the growth is still expected in countries that already have operating NPPs, especially in Asia, with China and India remaining the main centres of expansion while the Russian Federation will also remain a centre of strong growth. The 7–8% drop in projected growth for 2030 reflects an accelerated phase-out of nuclear power in Germany, some immediate shutdowns and a government review of the planned expansion in Japan, as well as temporary delays in expansion in several other countries.

Measures taken by countries as a result of the Fukushima Daiichi nuclear accident have been varied. A number of countries announced reviews of their programmes. Belgium, Germany and Switzerland took additional steps to phase out nuclear power entirely while others re-emphasized their expansion plans. Many Member States carried out national safety assessment reviews in 2011 (often called ‘stress tests’), and commitments were made to complete any remaining assessments promptly and to implement the necessary corrective action. In countries considering the introduction of nuclear power, interest remained strong. Although some countries indicated that they would delay decisions to start nuclear power programmes, others continued with their plans to introduce nuclear energy.

A Ministerial Conference on Nuclear Safety was convened by the Agency in June 2011. Its objectives were to discuss an initial assessment of the Fukushima Daiichi accident, to consider the lessons that needed to be learned, to help launch a process to enhance nuclear safety throughout the world and to consider ways of further strengthening the response to nuclear accidents and emergencies. The IAEA Action Plan on Nuclear Safety, which defines 12 main actions, was endorsed by the General Conference in September 2011.

In the 2011 edition of the Organisation for Economic Co-operation and Development (OECD)/Nuclear Energy Agency (NEA)–IAEA ‘Red Book’, estimates of identified conventional uranium resources at less than $130/kg U decreased slightly compared to the previous edition, as uranium production worldwide rose significantly, due largely to increased production in Kazakhstan. New resources were reported throughout 2011 for many uranium deposits in Africa, and commercial production was reported for the first time at the Honeymoon in situ leaching mine in Australia. Uranium spot prices, which at the end of 2010 had reached their highest levels in over two years ($160/kg U), fell after the Fukushima Daiichi nuclear accident and ended the year at $135/kg U.

The world's first Low Enriched Uranium (LEU) Reserve under the Agency's auspices, comprising 120 tonnes of LEU, was established in December 2010 at the International Uranium Enrichment Centre in Angarsk, Russian Federation. From 3 February 2011, the LEU Reserve in Angarsk has been available to Agency Member States. In addition, in March 2011, the Board of Governors approved a proposal for a Nuclear Fuel Assurance (NFA) by the United Kingdom, co-sponsored by the member countries of the European Union (EU), the Russian Federation and the USA. The NFA aims to ensure the supply of enrichment services and LEU for use in NPPs. Furthermore, during 2011 the Secretariat continued work on developing the administrative, financial, legal and technical arrangements for an Agency-coordinated LEU bank to serve as a supply of last resort for nuclear power generation. The Agency accepted an offer from Kazakhstan to host the bank at the Ulba Metallurgical Plant, and formal negotiations on the Host State Agreement began in 2012.

In the area of radioactive waste management, the Council of the EU adopted on 19 July 2011 a Directive establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. This Directive adopted a set of harmonized standards for all EU member countries that are based on the Agency's safety standards. In Sweden, the Swedish nuclear fuel and waste management company SKB submitted a license application to build a final disposal facility for spent nuclear fuel in Forsmark in March 2011. In the USA, the Blue Ribbon Commission on America's Nuclear Future issued, in July 2011, draft recommendations for developing a long-term solution to the management of the USA's spent fuel and nuclear waste. The final report was issued in January 2012.

In 2011, the Food and Agriculture Organization of the United Nations and the World Organisation for Animal Health (OIE) declared the global eradication of rinderpest, the most devastating infection of cattle, and for centuries a major cause of famine and poverty. After smallpox in 1980, this is only the second disease that has been successfully eradicated. Nuclear and nuclear-related techniques made an important contribution through the development and use of diagnostic tests such as the enzyme linked immunosorbent assay (ELISA), as developed by the IAEA Animal Production and Health Laboratory.

The globalization of trade in food along with animal movement has brought about an unprecedented increase of emerging and re-emerging animal as well as plant diseases and pests. During 2011, advances were made in utilizing nuclear techniques to address other transboundary animal diseases, including avian influenza (e.g. by tracing the origin of an outbreak using stable isotopes). Scientists are also looking into using irradiation to produce viral vaccines for foot-and-mouth disease, Rift Valley fever, influenza and other viral pathogens. The sterilization of insects as part of insect pest control programmes has traditionally used cobalt-60 or caesium-137 irradiators that produce gamma ray ionizing radiation. However, due to increasingly difficult shipping logistics scientists are exploring new ways of sterilizing insects, such as the use of self-contained low-energy X ray irradiators.

The Fukushima Daiichi accident substantially affected large areas of agricultural lands around the site and presented new challenges in terms of the development of agricultural countermeasures against radiation contamination. Although many of the options that were effectively used after past accidents (e.g. Kyshtym and Chernobyl) such as soil based and agrochemical remedial measures are being further tested and partially implemented in the Fukushima region, the specific conditions of the affected area have called for new approaches to ensure food safety and sustainable agricultural production.

In the area of environmental protection, the Fukushima Daiichi accident showed that a huge number of environmental samples need to be analysed very quickly to comply with regulatory limits and quality criteria. Rapid methods allow the time required for analysis to be reduced from days or weeks to hours or days. The validation and implementation of such methods is necessary above all for radionuclides which pose significant radiological concern in all potentially affected environmental media, as well as for food and animal feed.

The use of well characterized and validated sampling and analytical procedures is especially important in the case of transboundary environmental assessments. The Agency coordinates a worldwide network of analytical laboratories for the measurement of environmental radioactivity (ALMERA) in order to provide reliable and timely analysis of environmental samples in the event of an accidental or intentional release of radioactivity. The 2011 proficiency test organized by ALMERA focused on alpha, beta and gamma emitters in soil and water samples. In 2012, the focus will be on the quality and comparability of analyses of aerosol samples. As compared to the more common aerial and terrestrial in situ gamma spectrometry for environmental sampling, there is an obvious need to install in situ underwater monitoring through stationary and mobile high resolution gamma spectrometry of the coastal marine environment. This would allow for a reconstruction of liquid radioactive releases and rapid screening of water and sediment contamination.

In the area of human health, there is increasing recognition that appropriate nutrition during the first one thousand days of life from conception to two years of age can have a profound impact on a child's ability to grow and learn, and on the risk of developing chronic diseases, such as diabetes and heart disease, later in life. Nuclear techniques, such as stable isotope dilution, offer advantages in monitoring relatively small changes in body composition, and can be used to evaluate nutrition intervention programmes. In Chile, a successful use of stable isotope techniques to evaluate national intervention programmes led to the development of a Motor Development and Physical Activity Promotion Programme for children aged 6–24 months in 2011.

As part of the efforts to improve the quality of data management for radiotherapy, there is an increasing trend towards the use of 'record and verify systems' (RVS), a type of radiotherapy patient database management. In order to promote safe and effective patient treatment, in 2011 the Agency produced guidelines for sound quality management of RVSs, which had been endorsed by all major suppliers of radiotherapy equipment. Various approaches for diagnostic imaging are playing an ever increasing role in the detection and treatment of breast cancer. Recent advances in imaging technology coupled with developments in computer technology have fundamentally improved the processes of tumour targeting and radiation therapy planning. The Agency, through its Programme of Action for Cancer Therapy (PACT), in cooperation with partners such as the World Health Organization, continued to deliver comprehensive cancer control to Member States in 2011.

In the area of water resources, isotope techniques and related tools, together with newer mapping developments such as geographic information systems and geostatistical methods, are helping water managers to better delineate, quantify and visualize aquifers and groundwater bodies. In 2011, the use of low cost and easy-to-operate devices for the analysis of stable isotopes in water, based on laser spectroscopy, became a standard procedure for research groups worldwide. This has allowed them to be more independent in analysing stable isotopes for hydrological assessment, thus saving money and time. For example, isotopic studies to assess groundwater resources in the Santa Elena peninsula in Ecuador have provided information that has helped to increase the availability of water to many of the area's inhabitants.

Progress in nuclear imaging is closely linked to the production of new radionuclides with novel physical and chemical properties. In 2011, generator-produced radionuclides for positron emission tomography (PET) became increasingly more accessible in countries like Australia, China, France, Germany, India, Japan, the Republic of Korea, the UK and the USA because they can be produced in hospitals without an on-site cyclotron. Another trend observed in 2011 was that a number of manufacturers upgraded their cyclotron systems in order to achieve increased beam current and higher energies to meet the current demand for radionuclides used in such diagnostic techniques as PET and single photon emission computed tomography (SPECT), as well as therapeutic applications.

In the area of radiation technologies, the development of a highly effective vaccine for malaria in advanced stages of clinical trials was reported at the International Meeting on Radiation Processing in 2011. The vaccine is based on sporozoites that have been weakened by gamma irradiation. The vaccine prevents malaria blood-stage infection, protects an individual from the disease and blocks the transmission of the disease.

In another 2011 development, related to biofuels, the use of thermal hydrolysis combined with electron beam irradiation of sugar cane bagasse was shown to lead to increased yields of bioethanol. The use of radiation grafted fibrous polymer membranes, developed by the Quantum Beam Science Directorate of the Japan Atomic Energy Agency (JAEA) was successfully demonstrated to selectively remove radioactive caesium from two sites that were contaminated as a result of the Fukushima Daiichi accident. Radiotracers and nucleonic gauges are being increasingly used in mining mainly for the exploration and effective exploitation of natural resources.

A. POWER APPLICATIONS

A.1. Nuclear Power Today

In 2011, nuclear energy continued to play an important role in global electricity production. As of 31 December 2011, there were 435 nuclear power reactors in operation worldwide, with a total capacity of almost 369 GW(e)[1] (see Table A-1). This represents a decrease in total capacity of some 7 GW(e) compared to the end of 2010, which can be attributed mostly to a higher number of permanent shutdowns than grid connections. The new grid connections were: Ling Ao-4 (1000 MW(e)), Qinshan-2-4 (610 MW(e)) and China Experimental Fast Reactor (CEFR) (20 MW(e)) in China; Kaiga-4 (202 MW(e)) in India; Bushehr-1 (915 MW(e)) in the Islamic Republic of Iran; Chasnupp-2 (300 MW(e)) in Pakistan; and Kalinin-4 (950 MW(e)) in the Russian Federation.

The accident at the Fukushima Daiichi NPP had an impact on the overall number of construction starts on new reactors in 2011. The steady increase since 2003, which reached a peak of 16 construction starts in 2010, was halted in 2011 when construction started on only 4 NPPs: Chasnupp-3 and -4 in Pakistan and Rajasthan-7 and -8 in India.

In 2011, 13 reactors were officially declared as permanently shut down. These included not only units 1-4 at the Fukushima Daiichi NPP in Japan but also Biblis A and B, Brunsbüttel, Isar-I, Krümmel, Neckarwestheim-1, Philippsburg-1 and Unterweser in Germany. Oldbury A2 in the United Kingdom was also shut down due to the age of the reactor. This represents the highest number of shutdowns since 1990, when the Chernobyl accident had a similar effect. As a comparison, 2010 saw only one shutdown and 2009 three.

As of 31 December 2011, 65 reactors were under construction. This number, although smaller than in the previous year, remains very high. Moreover, as in previous years, expansion as well as near and long term growth prospects remain centred in Asia (cf. Table A-1). Indeed, of the total number of reactors under construction, no less than 44 are in Asia, as are 35 of the last 45 new reactors to have been connected to the grid.

Despite the Fukushima Daiichi accident, the recent trend of power uprates and of renewed or extended licences for many operating reactors continued in 2011 in many countries. In Canada, the Canadian Nuclear Safety Commission (CNSC) granted a five-year renewal of the operating licence for Gentille-2 in Quebec. In Finland, Finnish utility Teollisuuden Voima Oyj (TVO) completed in

[1] A 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 2011)[a]

Country	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2011		Total Operating Experience through 2011	
	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	5.0	66	7
Armenia	1	375			2.4	33.2	37	8
Belgium	7	5 927			45.9	54.0	247	7
Brazil	2	1 884	1	1 245	14.8	3.2	41	3
Bulgaria	2	1 906	2	1 906	15.3	32.6	151	3
Canada	18	12 604			88.3	15.3	618	2
China	16	11 816	26	26 620	82.6	1.9	125	6
Czech Republic	6	3 766			26.7	33.0	122	10
Finland	4	2 736	1	1 600	22.3	31.6	131	4
France	58	63 130	1	1 600	423.5	77.7	1 816	4
Germany	9	12 068			102.3	17.8	782	9
Hungary	4	1 889			14.7	43.3	106	2
India	20	4 391	7	4 824	29.0	3.7	357	3

TABLE A-1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2011)[a] (cont.)

Country	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2011		Total Operating Experience through 2011	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
Iran, Islamic Republic of	1	915			0.1		0	4
Japan	50	44 215	2	2 650	156.2	18.1	1 546	4
Korea, Republic of	21	18 751	5	5 560	147.8	34.6	381	1
Mexico	2	1 300			9.3	3.6	39	11
Netherlands	1	482			3.9	3.6	67	0
Pakistan	3	725	2	630	3.8	3.8	52	8
Romania	2	1 300			10.8	19.0	19	11
Russian Federation	33	23 643	10	8 188	162.0	17.6	1 058	4
Slovakia	4	1 816	2	782	14.3	54.0	140	7
Slovenia	1	688			5.9	41.7	30	3
South Africa	2	1 830			12.9	5.2	54	3
Spain	8	7 567			55.1	19.5	285	6
Sweden	10	9 326			58.1	39.6	392	6

TABLE A-1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2011)[a] (cont.)

Country	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2011		Total Operating Experience through 2011	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
Switzerland	5	3 263			25.7	40.9	184	11
Ukraine	15	13 107	2	1900	84.9	47.2	398	6
United Kingdom	18	9 953			62.7	17.8	1 495	2
United States of America	104	101 465	1	1 165	790.4	19.3	3 707	11
Total[b, c]	435	368 791	65	61 962	2 518.0	12.3%[d]	14 792	3

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

[b] Note: The total figures include the following data from Taiwan, China:
— 6 units, 5018 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 40.37 TW·h of nuclear electricity generation, representing 19.02% 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 (182 years, 1 month).

[d] Represents the *global* percentage of nuclear energy supplied in 2011.

2011 the latest of a series of refurbishments at unit 2 of the Olkiluoto NPP, which has raised the reactor's capacity (860 MW(e)) by 20 MW(e). These have brought Olkiluoto-2 total output to 880 MW(e), a one third increase from its original 660 MW(e). In France, the French Nuclear Safety Authority (Autorité de Sûreté Nucléaire, ASN) approved a lifetime extension of another ten years for the Fessenheim-1 NPP. In Mexico, early in the year the country's two reactors underwent a 20% capacity increase upon the completion of a four-year modernization project. In Spain, the Nuclear Safety Council (CSN) approved a ten-year operating licence extension for the Cofrentes NPP and the two units of the Ascó NPP. Furthermore, the two reactors at the Almaraz NPP were uprated by 70 MW(e). In Slovakia, the utility Slovenské elektrárne (SE) completed the modernization and uprate programme of both units at the Bohunice NPP. In the USA, the Nuclear Regulatory Commission (NRC) renewed the operating licences for an additional 20 years for: Vermont Yankee; Prairie Island-1 and -2; Kewaunee; Palo Verde-1, -2 and -3; Salem-1 and -2, and Hope Creek. This has brought the total number of approved licence renewals in the USA to 71 since 2000. Fifteen licence renewal applications are currently under review. Furthermore, 5 uprate applications were approved by the US NRC in 2011 and 20 power uprate applications are currently under review. Lastly, the first site selection for a new NPP after the Fukushima Daiichi accident was announced in October 2011 when the municipality of Pyhäjoki in Finland was selected by Fennovoima as the site of the country's third NPP.

The measures taken by countries across the world as a result of the Fukushima Daiichi accident have varied. A number of countries announced reviews of their nuclear power programmes, some took steps to phase out nuclear power entirely, whilst others re-asserted their intention to expand existing programmes. Although it did not change the policy of countries such as China, India and the Russian Federation, which are driving most of the global expansion of nuclear power, the accident raised questions about the future role of atomic energy in some countries. In Belgium, in October 2011 the decision taken in 2003 to shut down the country's oldest nuclear power reactors in 2015, which had been reconsidered in 2009, was reconfirmed and the Government proposed to double the special tax on nuclear power paid annually by the nuclear industry. In France, the future role of nuclear power was intensely debated. In Germany, the Government approved in June 2011 a legislative package leading to the permanent closure of Germany's nuclear reactors in a gradual phase-out to be completed by the end of 2022. Moreover, Germany's eight oldest reactor units were declared permanently shut down in August 2011. Italy, a country that was considering reviving its nuclear power programme after shutting down its last operating plant in 1990, determined after a June 2011 referendum that nuclear energy would no longer be an option for at least another five years, if not more. In

Japan, the Energy and Environment Council announced in July 2011 its intention to reduce the country's dependence on nuclear power. This was confirmed in a White Paper published by the Japanese Government in October 2011, which announced that Japan's reliance on nuclear energy would be reduced as much as possible in the medium and long term future and that a new energy policy would be developed. As of the end of November 2011, less than 20% of Japan's nuclear generating capacity was in operation. In Switzerland, the Senate voted in September 2011 to approve a motion for a phase-out of nuclear power by 2034. A public referendum on the issue is anticipated before the decision becomes final.[2]

Nonetheless, despite these recent developments, nuclear power remains an important option not only for countries with existing nuclear power programmes, but also for developing countries with growing energy requirements. While some countries have indicated that they will defer their decisions on whether or not to start nuclear power programmes, others are continuing with their plans to introduce nuclear energy, incorporating the lessons learned from the Fukushima Daiichi accident as the lessons emerge. The Islamic Republic of Iran commissioned its first NPP in September 2011. Several countries took concrete steps toward their first NPPs in 2011. The United Arab Emirates and Turkey are advancing their programmes with vendors from the Republic of Korea and the Russian Federation, respectively. In October 2011, Belarus signed a contract for the construction of two nuclear power reactors with the Russian Federation's Atomstroyexport (ASE). In November 2011, Bangladesh signed an intergovernmental agreement with the Russian Federation regarding the supply of two 1000 MW(e) reactors as well as fuel supply, take-back of spent fuel, training and other services. Also in November, Vietnam signed a loan agreement with the Russian Federation regarding financing for Vietnam's first NPP.

In 2011, Integrated Nuclear Infrastructure Review (INIR) missions were conducted by the Agency in Bangladesh and the UAE. The IAEA Action Plan on Nuclear Safety, which was adopted by the General Conference in September 2011, also encourages newcomer countries to incorporate the lessons learned from the Fukushima Daiichi accident in their infrastructure planning, and to invite review services, such as INIR missions, before commissioning their first NPPs. Throughout 2011, the Agency continued to offer Member States a broad range of assistance and support services including guidance and standards, technical assistance, review services, training, capacity building and knowledge networks, many of which are being reviewed to take into account the lessons from Fukushima. As a small number of countries advance their plans and strive to

[2] In addition, Taiwan, China, announced in November 2011 a new nuclear energy policy of phasing out nuclear power although no specific time frame has been outlined.

become 'knowledgeable customers', Agency assistance, especially for new owner/operator organizations, is increasing.

A.2. Projected Growth for Nuclear Power

The Agency publishes annually two updated projections for the global growth in nuclear power: a low projection and a high projection. The 2011 updates allow for the effects of the Fukushima Daiichi accident. In the 2011 updates, the projected global nuclear power capacity in 2030 is 7–8% lower than what was projected before the accident. Therefore, globally the accident is expected to slow or delay the growth of nuclear power, but not to reverse it. In the updated low projection, the world's installed nuclear power capacity grows from 369 gigawatts (GW(e)) at the end of 2011 to 501 GW(e) in 2030, down 8% from what was projected last year. In the updated high projection, capacity grows to 746 GW(e) in 2030, down 7% from last year's projection. Nevertheless, the number of nuclear reactors operating in 2030 would foreseeably increase by about 90 in the low projection and by about 350 in the high projection, from the total of 435 reactors at the end of 2011. Most of the growth is expected to occur in countries that already have operating NPPs.

As in previous years, the projected growth is greatest in the Far East. From 81 GW(e) at the end of 2010, capacity grows to 180 GW(e) in 2030 in the low projection and to 255 GW(e) in the high. These levels are, however, lower than last year's projections by 17 GW(e) and 12 GW(e) respectively.

Western Europe shows the biggest difference between the low and high projections. In the low projection, the region's nuclear power capacity drops from 123 GW(e) at the end of 2010 to 83 GW(e) in 2030. In the high projection, nuclear power grows to 141 GW(e), although that is still 17 GW(e) below the growth projected last year. In North America, the low case projects a small decline, from 114 GW(e) at the end of 2010 to 111 GW(e) in 2030. The high projection posits an increase to 149 GW(e), which is still 17 GW(e) below last year's projection.

Other regions with substantial nuclear power programmes are Eastern Europe (including the Russian Federation) and the Middle East and South Asia (including India and Pakistan). Nuclear power expands in these regions in both the low and high projections to only slightly lower levels than those projected last year. The same is true for Africa, Latin America and South East Asia, which have smaller programmes.

The Agency's low projection assumes that current trends continue with few changes in policies affecting nuclear power. But it does not necessarily assume that all national targets for nuclear power will be achieved. It is a conservative but

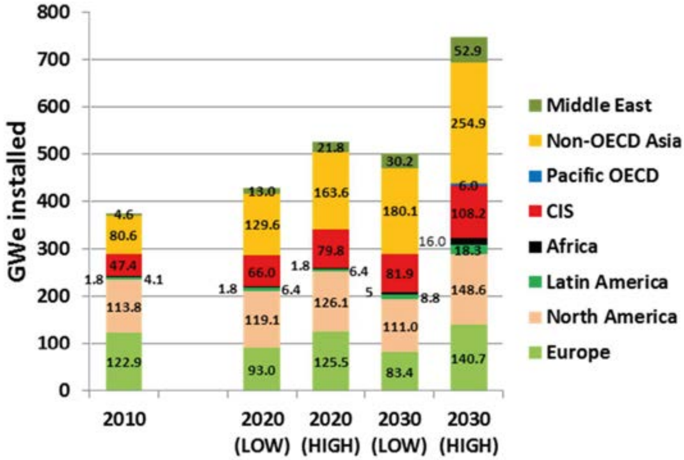

FIG. A-1. Development of regional nuclear generating capacities 2010–2030, low and high 2011 IAEA projections.

plausible projection. As for the high projection, it assumes that the current financial and economic crises will be overcome relatively soon and that past rates of economic growth and electricity demand will resume, notably in the Far East. Furthermore, the high projection assumes stringent global policies to mitigate climate change.

The continued growth envisaged by both the low and high projections suggests that the factors that contributed to increasing interest in nuclear power before the Fukushima Daiichi accident have not changed. These include increasing global demand for energy, as well as concerns about climate change, volatile fossil fuel prices and security of the energy supply.

The OECD's International Energy Agency (IEA) also publishes projections of the global growth in nuclear power. The IEA's *World Energy Outlook 2011* presents four cases of interest. Although the main report focuses on three scenarios, referred to respectively as the "current policies scenario", the "new policies scenario" and the "450 scenario" (where 450 refers to limiting the atmospheric concentration of greenhouse gases to 450 parts per million), the Fukushima Daiichi accident prompted the IEA to explore the implications of a substantial shift away from nuclear power in an additional scenario, a "low-nuclear scenario". The low nuclear case assumed that no new reactors would be built in OECD Member States, and that outside the OECD only half of the additional reactors envisaged in the new policies scenario would be built. It was also assumed that the operating lifespan of existing nuclear plants would be shortened. The resulting projected decrease in nuclear power led to a modest

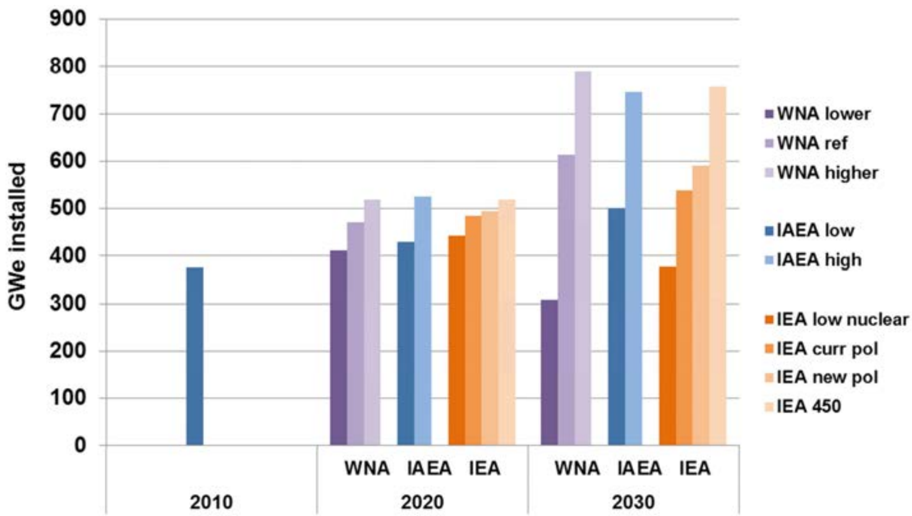

FIG. A-2. Comparison of nuclear power projections by the IAEA (blue), the World Nuclear Association (WNA; purple) and the International Energy Agency's "World Energy Outlook 2011" (IEA; orange).

increase in the share of electricity produced by renewable sources as well as significant projected increases in coal consumption, natural gas consumption, energy prices and greenhouse gas emissions (GHGs). These increased emissions would make it all but impossible to keep the rise in global mean temperature below two degrees Celsius relative to preindustrial levels, triggering what is now considered in climate science as dangerous anthropogenic interference with the climate system. Figure A-2 compares the Agency's projections, the IEA scenarios, and projections by the World Nuclear Association (WNA).[3] The IAEA's low projection, the IEA's current policies scenario and the WNA's reference scenario all use similar 'business-as-usual' assumptions and produce comparable results. The high scenarios from the organizations are also comparable, as are the low nuclear scenarios of the IEA and WNA.

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[3] *The Global Nuclear Fuel Market: Supply and Demand 2011–2030*, WNA, London, 2011.

A.3. Fuel Cycle[4]

A.3.1. Uranium resources and production

Every two years the IAEA and the OECD/NEA publish the so-called 'Red Book', *Uranium: Resources, Production and Demand*. The most recent edition was published in July 2012. The 2011 edition 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 previous edition's estimate. In addition, there were an estimated 1.8 Mt U of identified conventional resources recoverable at costs between $130/kg U and $260/kg U, bringing total identified resources recoverable at a cost of less than $260/kg U to 7.1 Mt U. For reference, the spot price for uranium in 2011 fluctuated between $165/kg U and $169/kg U until March, representing a two-year high, before falling to $150/kg U after the Fukushima Daiichi accident. The spot price gradually dropped off to $132/kg U in August, but by the end of the year it had climbed back to $135/kg U.

Undiscovered resources include both resources that are expected to occur either in or near known deposits and more speculative resources that are thought to exist in geologically favourable yet unexplored areas. 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 previous edition (published in 2010). 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 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, Mauritania, Malawi, Mali, Namibia, Zambia and the United Republic of Tanzania — where uranium exploration efforts remained strong. The Mkuju River project in the United Republic of Tanzania reached an advanced stage of feasibility study. South America has also reported additional or new resources for Colombia, Guyana, Peru, and Paraguay.

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[4] More detailed information on Agency activities related to the nuclear fuel cycle is available in the relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2011), on the General Conference web site and at www.iaea.org/NuclearFuelCycleAndWaste.

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 and uranium in seawater. Very few countries currently report unconventional resources. Current estimates of potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonatite, black schist and lignite are of the order of 8 Mt U. Uranium Equities Limited ("UEQ") announced that their pilot plant for the recovery of uranium from phosphoric acid using an ion exchange technique was set to commence production in May 2012. If the technique is successful, commercial production is expected to start around 2015.

Worldwide resources of thorium have been estimated to be about 6 to 7 million tonnes. Although thorium has been used as fuel on a demonstration basis, substantial further work is still needed before it can be considered on an equal basis with uranium. In India, the site-selection process for the country's planned experimental thorium-fuelled 300 MW(e) Advanced Heavy Water Reactor (AHWR) started in 2011. The reactor is expected to become operational by 2020. However, full commercialization of the AHWR is not expected before 2030.

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

In 2010, uranium production worldwide was 54 670 t U, 6% higher than the 51 526 t U produced in 2009. Uranium production for 2011 is estimated to increase to about 57 230 t U. Australia, Canada and Kazakhstan accounted for 62% of world production in 2010, and these three countries, together with Namibia, Niger, the Russian Federation, the USA and Uzbekistan, accounted for 92% of total production. In Kazakhstan, uranium production in 2010 increased by more than 27% from the previous year, making it by far, and for the second year in a row, the world's top uranium producer (up from fifth place in 2003 and second place in 2008). Furthermore, Kazakhstan's total uranium production in 2011 is expected to have increased by 12% compared to 2010.

In September 2011, commercial production was reported for the first time at the in-situ leaching[5] mine at Honeymoon in Australia. Once fully operational, the

[5] Conventional mining involves removing ore from the ground, then processing it to remove the minerals being sought. In situ leaching (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.

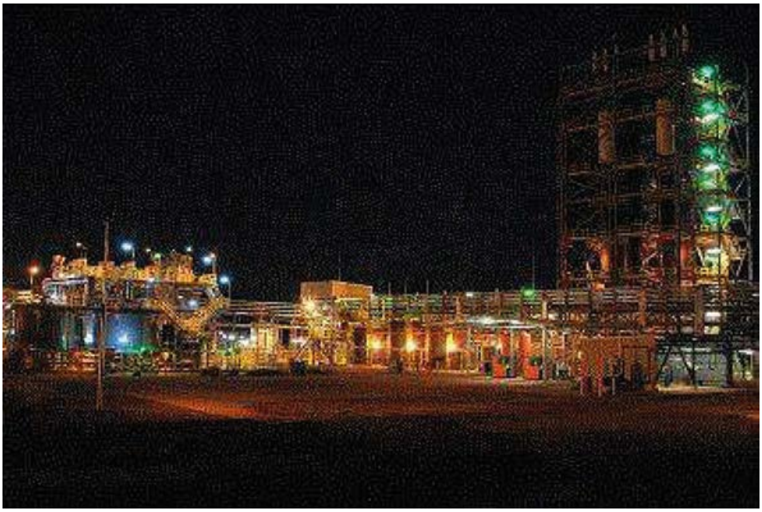

FIG. A-3. Honeymoon uranium mine, Australia, started commercial production in September 2011.

mine’s capacity is expected to reach 400 t U/year (275 t U in 2012). In addition, the Olympic Dam, a mining centre in South Australia, has obtained environmental clearance for its expansion project, which envisages a new open pit alongside the existing underground mine. The project will increase the mine’s annual capacity from the current 3800 t U to 19 000 t U. Furthermore, the Azelik uranium mine in Niger started trial operations in December 2010, with a full capacity of 700 t U/year expected to be reached in 2012.

Uranium production in 2010 covered only about 85% of the world’s estimated reactor requirements of 63 875 t U. The remainder was covered by five secondary sources: military stockpiles of natural uranium, stockpiles of enriched uranium, reprocessed uranium from spent fuel, mixed oxide (MOX) fuel with uranium-235 partially replaced by plutonium-239 from reprocessed spent fuel, and re-enrichment of depleted uranium tails (depleted uranium contains less than 0.7% uranium-235). At the estimated 2010 rate of consumption, the projected lifetime of the 5.3 Mt U of identified conventional resources recoverable at less than $130/kg U is around 80 years. This compares favourably to reserves of 30–50 years for other commodities (e.g. copper, zinc, oil and natural gas).

Based on projections available in 2010, the world annual reactor-related uranium requirements were projected to rise to between 97 645 t U and 136 835 t U by 2035. Currently projected primary uranium production capabilities including existing, committed, planned and prospective production centres could satisfy projected world uranium demand until 2028, based on the high end of this range, or until 2035, based on the low end.

A.3.2. Conversion, enrichment and fuel fabrication

Six countries (Canada, China, France, the Russian Federation, the UK and the USA) operate commercial scale plants for the conversion of triuranium octaoxide (U_3O_8) to uranium hexafluoride (UF_6), and small conversion facilities are in operation in Argentina, 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 75 000 tonnes of natural uranium (t U as UF_6) per year. However, major changes in the area are expected in France (Areva's Comurhex II) and the USA (the Honeywell Metropolis Works plant). Total current demand for conversion services (assuming an enrichment tails assay of 0.25% U-235)[6] is in the range of 59 000 to 65 000 t U/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 (under the auspices of the China National Nuclear Corporation (CNNC)), France (AREVA), the Russian Federation (Rosatom) and the USA (USEC and URENCO). The URENCO Group operates centrifuge plants in Germany, the Netherlands, the UK and the USA. There are also small enrichment facilities in Argentina, Brazil, India, Islamic Republic of Iran, Japan and Pakistan.

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 (ACP). In October 2011, the AREVA Eagle Rock enrichment facility received its licence.

Argentina has been performing research and development work on new enrichment technologies, such as centrifuge and laser enrichment, at the same time as rebuilding its gaseous diffusion capacity at Pilcaniyeu.

Japan Nuclear Fuel Limited (JNFL) expects to begin the commercial operation of improved centrifuge cascades at Rokkasho village, Aomori Prefecture, in 2012 and to expand the current capacity of 150 000 SWUs/year to

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[6] The tails assay, or concentration of U-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.

1.5 million SWUs/year by 2020. A new enrichment plant in Japan using Russian centrifuge technology is planned under an agreement between Rosatom and Toshiba.

In June 2011, an agreement was reached on new global terms of trade for uranium enrichment and spent fuel reprocessing by 46 countries in the Nuclear Suppliers Group (NSG). According to the new guidelines, countries that want to obtain nuclear technology must meet a set of requirements, including: full compliance with the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), no citations by international nuclear regulators for safeguard deficits, compliance with IAEA safeguards agreements and adherence to international safety standards.

Current total world deconversion capacity in 2011 remained at about 60 000 t UF_6/year after three deconversion facilities began operation in 2010 — two in the USA (in Paducah, Kentucky, and Portsmouth, Ohio) and one in the Russian Federation (W-ECP in Krasnoyarsk).

There are now several competing suppliers for most fuel types. Total global fuel fabrication capacity remained at about 13 000 t U/year (enriched uranium in fuel elements and fuel bundles) for light water reactor (LWR) fuel and about 4000 t U/year (natural uranium in fuel elements and fuel bundles) for pressurized heavy water reactor (PHWR) fuel. For natural uranium PHWR fuel, uranium is purified and converted to uranium oxide (UO_2) in Argentina, Canada, China, India and Romania. The current annual demand for LWR fuel fabrication services remained at about 7000 tonnes of enriched uranium in fuel assemblies, but is expected to increase to about 9500 t U/year by 2020. As for PHWRs, requirements accounted for 3000 t U/year. Expansion of current facilities is under way in China and new fabrication facilities are planned in Kazakhstan and in Ukraine. The planned fabrication facility in Kazakhstan, with an expected capacity of 1200 t U/year, is a joint venture by AREVA and Kazatomprom, and is scheduled to be completed in 2014.

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, is licensed to fabricate 150 t of RepU into fuel per year and PWR assemblies of this type have already been delivered to Belgian, French and UK reactors.

The current 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 ones in Japan and the Russian Federation. In Japan, JNFL is building a new MOX fuel manufacturing facility (130 t HM MOX) at Rokkasho, and completion is planned for March 2016. 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. In the UK, a new MOX fabrication facility is being added to the Sellafield MOX Plant (SMP) to enable the fulfilment of new, long term contracts for MOX supply. Additional MOX fuel fabrication facilities are under construction in the USA to use surplus weapon-grade plutonium. Worldwide, approximately 30 LWRs currently use MOX fuel.

Assurance of supply

The world's first LEU Reserve under the Agency's auspices was established in December 2010, located at the International Uranium Enrichment Centre in Angarsk, in the Russian Federation. The LEU Reserve, comprising 120 tonnes of LEU, with one-third of the material at an enrichment level of 4.95%, was verified by IAEA safeguards inspectors in December 2010. Currently valued at more than $300 million, the LEU Reserve is available to IAEA Member States whose supplies of LEU are disrupted for reasons unrelated to technical or commercial considerations. The LEU will be provided by the IAEA to eligible Member States for nuclear power generation at market price and the proceeds shall be used to replenish the LEU stock. The Russian Federation is covering the cost of the LEU in storage, as well of maintenance, safety, security and safeguards. The Agreement between the Government of the Russian Federation and the IAEA regarding the establishment on the territory of the Russian Federation of a Physical Reserve of LEU and the Supply of LEU therefrom to the IAEA for its Member States, signed in Vienna on 29 March 2010, entered into force on 3 February 2011. The LEU Reserve in Angarsk has been available for IAEA Member States from that date on.

In March 2011 the IAEA Board of Governors approved a proposal for the Assurance of Supply of Enrichment Services and Low Enriched Uranium for Use in Nuclear Power Plants (NFA) by the United Kingdom, co-sponsored by the Member States of the European Union, the Russian Federation and the United States of America. This introduced a draft 'Model NFA Agreement' by which a State supplying LEU or enrichment services could agree not to interrupt supplies to recipients that comply with international obligations and published export licensing standards. The proposal was originally tabled by the United Kingdom in 2007 and was further developed in 2009.

In addition, in December 2010, the Board of Governors approved the establishment of an IAEA LEU bank, i.e. a physical stock of LEU which will be under the Agency's jurisdiction and control. The purpose of this LEU bank is to serve as a mechanism to back up the commercial market without distorting it, in the event that a Member State's supply of LEU is disrupted and cannot be restored by commercial means, provided that the State in question fulfils the eligibility criteria established by the Board. During 2011, the IAEA Secretariat continued work on developing the necessary administrative, financial, legal and technical arrangements. In May 2011, the IAEA circulated criteria for the selection of a Host State with a suitable site to locate the IAEA LEU Bank and invited Member States to submit expressions of interest in hosting the IAEA LEU Bank. Kazakhstan was the only Member State to formally submit such an expression of interest, and the Agency accepted Kazakhstan's offer to host the bank at the Ulba Metallurgical Plant. Formal negotiations on the Host State Agreement began in 2012, and IAEA teams visited the Ulba site in 2012 for detailed assessments of requirements for upgrades to safety and security. 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 2011, pledges had been fully paid by Norway ($5 million), the United States (approximately $50 million) and the NTI ($50 million); the EU had paid €10 million of its €25 million pledge and arrangements were being finalized with Kuwait ($10 million) and the United Arab Emirates ($10 million).

The rights of Member States, including that of establishing or expanding their own production capacity in the nuclear fuel cycle, will remain intact and will not in any way be compromised or diminished by the establishment of such mechanisms for the assurance of supply.

In August 2011, the American Assured Fuel Supply (AFS) also became available in the USA. It comprises 230 tonnes of LEU with an enrichment of 4.95%.

A.3.3. Back end of the nuclear fuel cycle

In 2011 about 10 500 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 2011 is approximately 350 500 t HM, of which about 240 000 t HM are stored in at-reactor (AR) or away-from-reactor (AFR) storage facilities. Less than a third of the cumulative amount of spent fuel discharged globally, about 100 000 t HM, has already been reprocessed. In 2011, the global commercial reprocessing capacity, spread across four countries (France, India, Russian Federation and the UK), was about 4800 t HM/year.

By mid-2011, China had completed the cold testing of its 50 t HM/year pilot reprocessing plant, as well as the 5% hot test operation (5% spent fuel solution +95% simulated solution). Research and development work is continuing to provide technical support for stable operations of the pilot reprocessing plant. China is also planning to build a commercial reprocessing facility and the siting process is under way. Furthermore, the demonstration of the direct use of recycled uranium as fuel in a CANDU reactor has been completed at the Qinshan NPP. In 2010 and 2011, 24 CANDU 37-element fuel bundles containing natural uranium equivalent (NUE), which is obtained by mixing reprocessed and depleted uranium, were irradiated in Qinshan Unit 1, and they demonstrated good fuel performance.

In India, construction of the Fast Reactor Fuel Cycle Facility (FRFCF) at Kalpakkam continues. The Facility includes a fuel fabrication and reprocessing plant, a reactor core sub-assembly plant, a reprocessed uranium oxide plant and a waste management plant to serve the upcoming 500 MW(e) Prototype Fast Breeder Reactor (PFBR).

In Japan, construction of the 800 t HM/year commercial reprocessing plant at Rokkasho was almost complete when work was suspended as a consequence of the earthquake and tsunami on 11 March 2011.

A.3.4. Radioactive waste management and decommissioning

The global radioactive waste inventory reported as being in storage at the end of 2010 (the most recent year available) reached approximately 61.4 million m^3 of short lived, low and intermediate level waste (LILW–SL)[7], 13.9 million m^3 of long lived, low and intermediate level waste (LILW–LL), and 423 000 m^3 of high level waste (HLW) (see Table A-2).

The total cumulative disposal of radioactive waste up to the end of 2010 included approximately 24.7 million m^3 of LILW–SL; 625 000 m^3 of LILW–LL; and the disposal of approximately 4000 m^3 of HLW, primarily from Chernobyl. The low ratio of disposal to storage for LILW–LL and HLW reflects the general lack of disposal capacity for these two waste classes worldwide.

Disposal facilities for all categories of radioactive waste are operational or are under development worldwide. Disposal options include trench disposal of very low level waste (VLLW; France, Spain, Slovakia, Sweden), naturally occurring radioactive material (NORM) waste (Malaysia, Syrian Arab Republic) and low level waste (LLW) in arid areas (Islamic Republic of Iran, South Africa, USA); near surface engineered structures for LLW (Belgium, Bulgaria, Czech Republic, France, India, Japan, Lithuania, Romania, Slovakia, Slovenia, Spain, UK); intermediate depth disposal of low and intermediate level waste (LILW; Czech Republic, Hungary, Japan, Republic of Korea, Norway) and NORM waste (Norway); borehole disposal of LLW (USA) and disused sealed radioactive sources (DSRS; Ghana, Malaysia, Philippines); and deep geological facilities

[7] The apparent increase in LILW–SL storage since the *Nuclear Technology Review 2011* is due to the inclusion of new data on the storage of low level liquid radioactive waste.

TABLE A-2. GLOBAL ESTIMATE OF RADIOACTIVE WASTE INVENTORY FOR 2010 (MOST RECENT DATA)[a]

Waste class[b]	Storage[c] (m^3)	Cumulative disposal (m^3)
Short lived low and intermediate level waste (LILW–SL)	61 381 000	24 720 000
Long lived low and intermediate level waste (LILW–LL)	13 901 000	625 000
High level waste (HLW)	423 000	4 000

Source: NEWMDB (2011), and other references.[d]

[a] The figures in Table A-2 are estimates and should not be mistaken for an accurate accounting of radioactive waste stocks currently managed worldwide. In addition to the usual possible discrepancies in the estimated storage quantities from year to year due to mass and volume changes in waste during the waste management process, the total quantity of accounted waste continuously rises as additional Member States are added to the Agency's Net Enabled Waste Management Database (NEWMDB), and as these provide missing data, including data from previous years.

[b] The inventory in NEWMDB is currently reported according to the recommendations for waste classification contained in the Safety Guide *Classification of Radioactive Waste* (IAEA Safety Series No. 111-G-1.1, Vienna, 1994). These have been recently superseded by a new classification scheme outlined in the General Safety Guide *Classification of Radioactive Waste* (IAEA Safety Standards Series No. GSG-1, Vienna, 2009). Data in NEWMDB are currently being converted in accordance with the new classification scheme.

[c] Wastes are treated and conditioned and taken through various handling steps prior to storage or disposal. The mass and volume of radioactive waste are therefore continuously changing during the process of pre-disposal management. This can lead to discrepancies in estimated storage quantities from year to year.

[d] Sources in addition to NEWMDB include publicly available National Reports to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, and other published data.

designated for LILW (Germany, USA) and HLW and/or spent fuel (Finland, France, Sweden).

Belgium intends to dispose of low and medium activity, short lived waste in a surface disposal facility in the municipality of Dessel. The Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) initiated a safety case, including an environmental impact assessment (EIA) in 2009 which will be finalized in 2012. ONDRAF/NIRAS will then submit an application for a construction and operation licence. The facility is scheduled to be operational in 2016.

In Bulgaria, a spent fuel storage facility was officially opened in May 2011 at the Kozloduy NPP.

In Canada, in April 2011, Ontario Power Generation (OPG) formally submitted an environmental impact statement (EIS) and the final documentation for a licence to prepare a site and to construct a deep geological repository for LILW in the vicinity of the Bruce nuclear site. Currently, a feasibility study is under way to assess the suitability of the Chalk River Laboratories (CRL) site to host a Geologic Waste Management Facility (GWMF), a repository nominally 500 m deep in which it is proposed to isolate and contain LLW and intermediate level waste (ILW) derived from the CRL site.

In Denmark, six potential locations for a repository for the country's LILW were identified in a study submitted to the Government in May 2011.

In France, the Cigéo project to dispose of highly radioactive waste, primarily from nuclear power plants and the reprocessing of their spent fuel, will enter into its industrial design phase in 2012.

In Olkiluoto, Finland, the nuclear waste management company Posiva is building the ONKALO underground rock characterization facility, ONKALO, which reached final disposal depth in 2010. Posiva intends to submit the repository construction licence application for this site to the Finnish Government at the end of 2012 and to commence final disposal in 2020.

In Ghana, a radioactive waste disposal facility was inaugurated at the Ghana Atomic Energy Commission (GAEC) in Accra for the purpose of safely and securely storing radioactive sources that are no longer functional or needed.

In Germany, in October 2010 investigations at the exploration mine Gorleben, a prospective site for HLW/spent nuclear fuel (SNF), were restarted after a ten-year moratorium. These are being carried out by DBE. The company is also responsible for the ongoing reconstruction of the Konrad mine into a national repository for LILW. This facility will be 1000–1100 m below ground surface and the start of operations is expected in 2019. In February 2011, backfilling of the central part of the facility was completed. BfS, the licensee for the Morseleben repository, has submitted a closure licence application.

The Public Limited Company for Radioactive Waste Management (PURAM) in Hungary is about to complete the construction of a subsurface (about 200 m) repository at Bátaapáti for LILW from NPPs. Whilst the storage area at the surface part of the facility is already in operation, disposal commissioning is scheduled for 2012. A similar disposal complex is expected to be completed in Gyungju, Republic of Korea, in 2012. The storage section of the facility has been in operation since December 2010.

In Lithuania, the State Nuclear Power Safety Inspectorate (VATESI) has issued a licence to the Ignalina NPP for the construction of solid radioactive waste retrieval and pretreatment facilities.

In the Russian Federation, the construction of a new dry spent fuel storage facility at the Mining Chemical Combine (MCC) Zheleznogorsk, in the Krasnoyarsk region was initiated in 2003. The construction of the first stage of the facility, with an RBMK spent fuel capacity of 8 100 tonnes, was completed in December 2011.

On 16 March 2011, the Swedish Nuclear Fuel and Waste Management Company (SKB) submitted a licence application to the country's authorities for the construction of a final disposal facility for SNF in Forsmark, in the municipality of Östhammar, and an encapsulation plant in Oskarshamn. SKB estimates that operations could commence by 2025.

A new radioactive waste disposal facility was opened in November 2011 near Andrews County, Texas, in the USA. It is operated by Waste Control Specialists; shallow land trenches are licensed to accept A, B and C class LLW.

Also in the USA, the Blue Ribbon Commission on America's Nuclear Future, established in January 2010, issued draft recommendations for developing a long term solution to manage the USA's spent nuclear fuel and nuclear waste in July 2011.[8] The final report was issued in January 2012.

The Council of the European Union (EU) approved, on 19 July 2011, a Council Directive (2001/70/EURATOM) for the responsible and safe management of spent fuel and radioactive waste that adopted a set of harmonized standards for EU Member States, based on the IAEA standards on waste management and disposal. The Directive includes a requirement for EU Member States to establish and maintain national programmes including inter alia the concepts or plans and technical solutions for spent fuel and radioactive waste management from generation to disposal. Member States have to notify their national programmes to the European Commission (EC) and to report to the EC on the implementation of the Directive not later than 23 August 2015 and every three years thereafter.

The safe and secure management of high activity sources still pose particular problems as significant constraints, mainly financial, prevent their easy repatriation at the end of their useful life. A number of successful operations have been conducted to condition and remove disused sealed radioactive sources (DSRS) from user premises and bring them under control either by moving them to a national radioactive waste storage facility or in some cases removing them from the country entirely. Singapore no longer has any disused high activity

[8] More information is available at http://brc.gov/.

sources in the country as of September 2011 when the last high activity disused sealed radioactive source was removed for recycling. A similar action was carried out in Madagascar where a teletherapy source of French origin was repatriated back to France in October 2011.

Legacy radioactive waste

Significant work is being carried out to eliminate the nuclear legacy of the Cold War. For some fifteen years now, the Agency's Contact Expert Group for International Radioactive Waste Projects in the Russian Federation (CEG) has proven an efficient forum for information exchange and coordination of nuclear legacy programmes in the Russian Federation. By the end of 2011, the Russian Federation, with significant help from CEG partners, had defuelled and dismantled 196 of 200 decommissioned nuclear submarines. The defuelled submarine reactor units are in the process of being sealed and placed in a long term storage facility. The safe removal of spent nuclear fuel and waste from former navy bases is now the CEG's priority. The creation of two regional radioactive waste conditioning and storage centres is under way. 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 119 remaining.

Large scale programmes for the processing of legacy waste are being pursued by Canada (Chalk River Nuclear Laboratory), the Russian Federation (Mayak and Siberian Chemical Combine) and the USA (Savannah River National Laboratory). At Hanford, USA, the construction of the world's largest waste treatment plant (WTP) is about 50% complete. The plant has a budget of $12 billion and is expected to start operations in 2019. It will process and stabilize about 200 000 m^3 of a variety of complex legacy wastes by pre-treatment followed by vitrification.

Radioactive waste generated by the Fukushima Daiichi accident

Radioactive waste generated by the Fukushima Daiichi accident requires not only short term measures that were taken at the NPP site after the accident but also long term measures for life-cycle management of all waste, on- and off-site.

In response to a request made by the Government of Japan, the Agency organized a fact-finding mission which took place from 7–15 October 2011 to support the remediation of large contaminated areas off-site of the Fukushima Daiichi NPP. The mission objectives were to provide assistance to Japan's plans to remediate large areas contaminated by the accident; to review Japan's remediation strategies, plans and activities, including contamination mapping; and to share its findings with the international community as part of the joint effort to broadly disseminate lessons learned from the accident. The mission report, published in November 2011, highlighted nine areas of important progress and offered advice on twelve points where the mission team felt that current practices could be improved. The advice covers improvements in strategy, plans and specific remediation techniques, taking into account both international standards and experience from remediation programmes in other countries.

The remediation of the contaminated land in the vicinity of Fukushima will require storage facilities to be built to hold some 15–28 million m^3 of waste. The storage facilities will require an area of 3–5 km^2 and need to be available within 3 years. Final disposal options for this waste will need to be considered in due course.

The accumulation of large volumes of water contaminated with caesium-134 and caesium-137 in the basements of reactors, turbine buildings and trenches led to a critical situation with impending danger of overflow and leaks to the environment. In addition to the large volumes involved, a major challenge in treating this contaminated water lies in the presence of oil and high concentrations of sodium ions from seawater. The existing treatment facilities were damaged and not available for use. The situation was brought under control by swiftly mobilizing local and international support to set up efficient high-throughput treatment systems that have successfully treated more than 150 000 m^3 of the wastewater. A range of technologies have been deployed in a skid-mounted transportable configuration, including flocculation–precipitation, zeolite ion exchange, reverse osmosis and evaporation. Decontaminated and desalinated water has been successfully recycled to cool the damaged reactor cores. Water in the spent fuel storage pools located in the reactors is also being treated by deploying smaller capacity mobile systems. Future challenges arising from this effort relate to the management of highly radioactive chemical sludge and spent zeolite columns.

The defuelling of the damaged reactors will require the development of special tools, handling equipment and solutions for the processing of problematic transuranic (TRU) waste. The development of tools and methods to manage such waste is expected to take some time and will require a high level of expertise.

Decommissioning

Worldwide power reactor decommissioning statistics changed marginally in 2011. As of December 2011, 124 power reactors were shut down. Dismantling was completed for one reactor in 2011 — namely, the Windscale advanced gas cooled reactor (AGR) in the UK, which brings the number of shut down and fully dismantled power reactors up to 16. Fifty power reactors were in the process of being dismantled, 49 were being kept in safe enclosure mode, 3 were entombed, and 6 did not yet have specified decommissioning strategies.

The dismantling of the Windscale AGR, an experimental nuclear plant that was built in the 1960s, was completed in 2011 after 12 years of difficult work. The project has provided a blueprint for the decommissioning of the 14 other AGRs around the UK as they come to the end of their useful lives.

Studsvik of Sweden signed in late 2011 a contract with the UK's LLW Repository Ltd (LLWR) for the transport of five old heat exchangers, each weighing over 300 tonnes, from the decommissioned Berkeley Magnox NPP to Sweden and their dismantling, during which up to 90% of their metal content will be recycled.

The cost in the USA of nuclear dismantling and decommissioning has been estimated at $69.3 billion. Decommissioning funds in the USA have proved to be adequate. The transfer of ownership of the Zion NPP from Exelon Corporation to Energy Solutions in 2010 demonstrated that the funds allocated by law to pay for future decommissioning activities are sufficient for their actual implementation.

A.4. Safety[9]

In 2011, discussions on NPP safety were dominated by the need to identify and apply the lessons that could be learned from the accident at the Fukushima Daiichi NPP, caused by the extraordinary natural disasters of the earthquake and tsunami that struck Japan on 11 March 2011.

A Ministerial Conference on Nuclear Safety was convened by the Agency in June 2011 to discuss an initial assessment of the Fukushima Daiichi accident, to consider the lessons that need to be learned, to help launch a process to enhance nuclear safety throughout the world and to consider ways to further strengthen the response to nuclear accidents and emergencies. Many Member States carried out reviews in 2011 as part of national safety assessments (often called 'stress tests'), and commitments were made to complete any remaining assessments promptly and to implement the necessary corrective action.

The preliminary insight gained from the accident was the need for operators of NPPs worldwide to review and strengthen, as needed: (a) protective measures against extreme hazards like tsunamis; (b) power and cooling capabilities in the event of severe accidents; (c) preparations to manage severe accidents; and

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[9] Additional information on nuclear safety can be found in the *Nuclear Safety Review 2012* or in the *IAEA Annual Report 2011*.

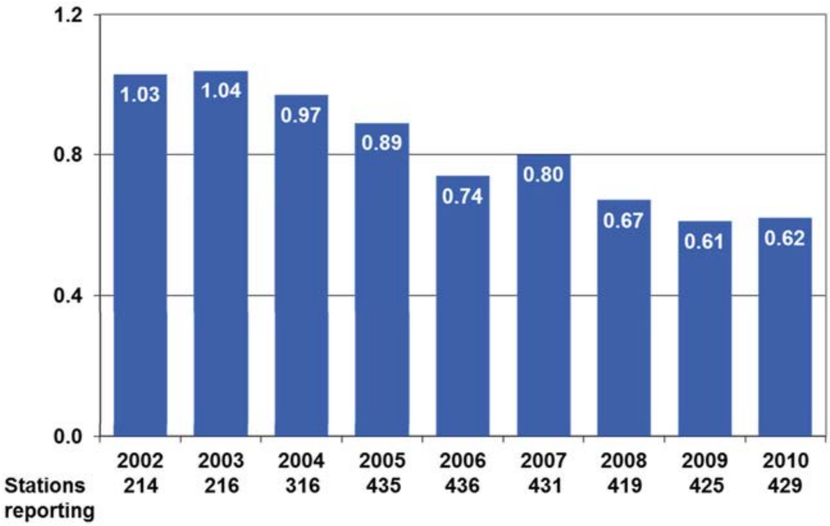

FIG. A-4. Total number of unplanned scrams, including both automatic and manual scrams, that occur per 7000 hours of critical power reactor operation (Source: IAEA).

(d) the design bases of plants, i.e. the assumptions about a predetermined set of accidents to be taken into account.

Although there are lessons yet to be learned, action plans applying the accident's preliminary lessons were already developed at both the national and international level. The IAEA Action Plan on Nuclear Safety defines a programme of work to strengthen the global nuclear safety framework. It was adopted by the General Conference in September 2011 and defines 12 main actions.[10]

Further lessons may be learned and, as appropriate, incorporated into these actions by updating the Action Plan. In December 2011, the Government of Japan announced that the reactors at the Fukushima Daiichi NPP had achieved a 'cold shutdown condition' and were in a stable state, and that the release of radioactive materials was under control.

Operationally, the level of NPP safety around the world remains high, as indicated by safety indicators collected by the IAEA and the World Association of Nuclear Operators (WANO). Figure A-4 shows the total number of unplanned scrams, including both automatic and manual scrams, that occur per 7000 hours of critical power reactor operation, compiled by the Agency in the Power Reactor

[10] 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*.

Information System (PRIS) database.[11] This indicator monitors performance in reducing the number of unplanned total reactor shutdowns and is commonly used to provide an indication of success in improving plant safety. As shown in Fig. A-4, steady improvements, although not as dramatic as those attained in the 1990s, have been achieved in recent years. Nevertheless, the gap between the best and worst performers is still large, and room for continued improvement exists. More detailed safety related information on cross-cutting nuclear topics and recent safety developments throughout 2011, beyond the focus on the Fukushima Daiichi accident, can be found in the *Nuclear Safety Review for the Year 2012*.

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[11] *http://prisweb.iaea.org*.

B. ADVANCED FISSION AND FUSION

Operating experience with existing reactors, together with advances in nuclear science and engineering, continually drive the development of new advanced reactor designs. This section summarizes such developments for reactor designs based first on nuclear fission and second on nuclear fusion.

B.1. Advanced Fission

B.1.1. Water cooled reactors

In Canada, the Canadian Nuclear Safety Commission (CNSC) is continuing a pre-project design review of the 700 MW(e) Enhanced CANDU-6 design, which incorporates several innovations from the CANDU-9 design as well as taking into account recent experience with CANDU-6 units built in China and the Republic of Korea. Candu Energy has also continued development of the advanced CANDU reactor (ACR-1000), which incorporates very high component standardization and slightly enriched uranium to compensate for the use of light water as the primary coolant. In January 2011, the CNSC completed all three phases of the pre-project design review for the ACR-1000, making it the first advanced nuclear power reactor to have completed such a design review by the CNSC. Atomic Energy of Canada Limited (AECL) is actively developing a CANDU supercritical water cooled reactor (SCWR), which will further Canada's leadership of the Generation IV International Forum's (GIF's) SCWR programme.

In China, 26 pressurized water reactors (PWRs) are under construction. These include 650 MW(e) and 1080 MW(e) evolutionary PWRs based on existing operating plant technology, as well as newer AP-1000 and European pressurized water reactor (EPR) designs. A new Ling Ao-4, a CPR 1000 design reactor, was connected to the grid on 3 May 2011. China continues to develop the CAP-1400 and CAP-1700 designs, which are larger scale versions of the AP-1000. At the same time, China continues to invest in research for the design of a Chinese SCWR.

In France, AREVA continues to market the 1600+ MW(e) EPR and to develop the 1100+ MW(e) ATMEA PWR, together with Mitsubishi Heavy Industries of Japan, and the 1250+ MW(e) KERENA boiling water reactor (BWR), in partnership with Germany's E.ON.

In India, five reactors are under construction, including three evolutionary 700 MW(e) pressurized heavy water reactors (PHWRs) and two 1000 MW(e) water cooled water moderated power reactors (WWERs). The Nuclear Power

Corporation of India Limited (NPCIL) has developed an evolutionary 700 MW(e) PHWR. The Bhabha Atomic Research Centre (BARC) is finalizing the design of a 300 MW(e) advanced heavy water reactor (AHWR), which will use thorium with heavy water moderation, a boiling light water coolant in vertical pressure tubes, and passive safety systems.

In Japan, two advanced boiling water reactors (ABWRs) are under construction at Ohma and Shimane-3 and more ABWRs are in the planning stage. Hitachi continues the development of 600, 900 and 1700 MW(e) versions of the ABWR, as well as the 1700 MW(e) ABWR-II. Mitsubishi Heavy Industries' 1700 MW(e) version of the advanced pressurized water reactor (APWR) for the US market, the US-APWR, is progressing through the US Nuclear Regulatory Commission design certification process. A European version of the APWR, the EU-APWR, is also under development and will be assessed for compliance with European utility requirements. Furthermore, Japan continues to pursue the development of an innovative SCWR design.

In the Republic of Korea, the construction of the first advanced power reactor, APR-1400, is progressing according to plan. A European version of the APR-1400, the EU-APR-1400, which will be assessed for compliance with European utility requirements, continues to be developed. The design certification process with the US Nuclear Regulatory Commission for the US version, the US-APR-1400, has begun, with the goal of achieving final certification in 2015. In parallel, development of the 1500 MW(e) APR+ and APR-1000 continued in 2011.

In the USA, in December 2011, the NRC amended the Westinghouse AP1000 Design Certification amendment, incorporating design updates and enhancements.

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

B.1.2. Fast neutron systems

Fast reactors have been under development for many years in several countries, primarily as breeders. Plutonium breeding, together with fuel reprocessing and recycling, allows fast reactors to extract 60 to 70 times more energy from uranium than thermal reactors do — a capability which would enable very substantial increases in nuclear power in the longer term. Fast reactors can also contribute to reducing plutonium stockpiles and reducing the required isolation time for high level radioactive waste by utilizing transuranic radioisotopes and transmuting some long-lived fission products.

In China, the 65 MW(th) (20 MW(e)) pool-type China Experimental Fast Reactor (CEFR), which reached criticality for the first time on 21 July 2010, was connected to the grid on 21 July 2011. The CEFR physics start-up programme is under way.

Construction of India's 500 MW(e) Prototype Fast Breeder Reactor (PFBR) at Kalpakkam is well under way: the safety, primary and internal vessels have been installed, and the reactor building is closed. Commissioning is planned for early 2013.

Japan is developing the 1500 MW(e) Japan Sodium Cooled Fast Reactor (JSFR) as part of its Fast Reactor Cycle Technology (FaCT) project. In the aftermath of the events of March 2011 at the Fukushima Daiichi nuclear power plant, Japan is re-evaluating the continuation of the programme and a decision on the continuation of the project is expected once the Government has reached consensus on its revised nuclear energy policy.

The Republic of Korea is carrying out an extensive research and development programme in support of the 600 MW(e) sodium cooled fast reactor (SFR) called KALIMER.

In the Russian Federation, which operates in Beloyarsk what is currently the most powerful existing commercial fast reactor (the BN-600), construction of the BN-800 fast reactor continues to progress. It is envisaged that construction will be completed in 2014 and commissioning will begin in the same year. Also, the Russian Federation launched in 2010 the Federal Target Programme "New Generation Nuclear Power Technologies for 2010–2015 and Future Trends up to 2020" aimed at developing an advanced sodium cooled fast reactor (SFR) (BN-1200), two innovative heavy liquid metal cooled fast reactors (the lead-cooled BREST-OD-300 and the lead–bismuth eutectic (LBE) cooled SVBR-100), as well as their related fuel cycles and a new sodium cooled multipurpose fast research reactor called MBIR.

Various industrial programmes have been recently launched in Europe, Japan, the Republic of Korea and the Russian Federation, with the goal of having new fast reactor demonstration plants and prototypes in operation by 2025–2030.

In order to meet long term European energy needs including security of supply, safety, sustainability and economic competitiveness, the EU — under its Strategic Energy Technology Plan (SET-Plan) — defined in November 2010 its technological pathway for developing fast neutron reactors. This pathway consists of: the SFR as a first track — based on previous experience with this design in Europe — and two alternative fast neutron reactor technologies to be explored on a longer timescale: the lead cooled fast reactor (LFR) and the gas cooled fast reactor (GFR). The related demonstration and implementation programme — the European Sustainable Nuclear Industrial Initiative (ESNII) — foresees the construction in France of the SFR prototype called ASTRID and of two demonstration plants, ALFRED and ALLEGRO, for the LFR and GFR alternative technologies respectively. The programme is also supported by the construction in Belgium of a fast spectrum subcritical irradiation facility called MYRRHA, which also serves as a pilot facility for the lead cooled fast prototype Alfred. To test subcriticality monitoring, a zero-power mock-up of MYRRHA, GUINEVERE, has been built and is being operated at the laboratories of the Belgian Nuclear Research Centre (SCK•CEN) in Mol.

B.1.3. Gas cooled reactors

In China, the implementation plan for the demonstration high temperature gas cooled reactor (HTGR) was approved by the State Council in February 2008. The project licence is under review.

In Japan, more rigorous tests — 90 days in total with 50 days at 950°C — of the high temperature engineering test reactor (HTTR) have been completed. The Japanese Government is considering the feasibility of connecting the HTTR to a hydrogen production system for the small scale production of hydrogen.

The Republic of Korea continues to invest in a number of test facilities for engineering testing of systems and components for a high temperature reactor (HTR) coupled with a hydrogen production facility. Process heat applications are also planned, with a number of industrial heat users collaborating with the nuclear research community to find optimal methods to produce heat and hydrogen from an HTR. The selection of a reactor concept is scheduled by 2015. The Nuclear Hydrogen Development and Demonstration (NHDD) project is receiving strong support from both industry and the Government.

In South Africa, plans for moving the pebble bed modular reactor (PBMR) into the construction phase were halted in 2010 as a result, inter alia, of funding constraints in the wake of the global financial crisis. The project remains under a ‘care and maintenance plan’ in order to protect the intellectual property and assets involved, until the Government decides on future actions.

In the USA, experimental testing of the safety of tri-structural isotropic (TRISO) fuel, as measured in terms of fuel failure rates during long periods of irradiation, continued at the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL). The goal of these experiments is to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating, transient and accident conditions, to support the development and validation of the PARFUME fuel performance and fission product release simulation code, and to provide irradiated TRISO fuel for post-irradiation examination (PIE) and safety/heat-up testing. PIE work and heat-up testing is continuing on irradiated TRISO fuel and compact specimens from the first fuel experiment (AGR-1). The second fuel experiment (AGR-2) was inserted into the ATR in June 2010 and is ongoing. The third and fourth experiments (AGR-3/4) have been combined into a single experimental test train, and include designed-to-fail TRISO particles that will provide fission product release data to validate simulation models, as well as irradiation performance information for TRISO fuel operating at higher temperatures. AGR-3/4 was inserted into the INL ATR in December 2011 and is being irradiated for two years. Graphite irradiation creep experiments are continuing in the INL ATR that will provide performance information for several commercial-grade nuclear graphite types. The second graphite creep experiment, AGC-2, was inserted into the ATR in February 2011 and irradiations are ongoing. The design review for the AGC-3 has been completed and fabrication will be completed in 2012. The Next Generation Nuclear Plant (NGNP) project funds are focused on continuing the TRISO and graphite irradiation campaigns, and creating a public-private partnership for the NGNP demonstration reactor's design, licensing and construction.

B.1.4. Small and medium sized reactors (SMRs)[12]

According to the classification adopted by the Agency, small reactors are reactors with an equivalent electric power of less than 300 MW(e) and medium sized reactors are reactors with an equivalent electric power of between 300 MW(e) and 700 MW(e). SMRs can provide an attractive and affordable nuclear power option for many developing countries with small electrical grids, insufficient infrastructure, limited investment capability or when energy production flexibility is required. SMRs are also of particular interest for cogeneration and many advanced future process heat applications.

At present, 13 SMRs are under construction in six countries: Argentina, China, India, Pakistan, the Russian Federation and Slovakia. Small and medium sized reactors are under development for all principal reactor lines including light water reactors (LWRs), heavy water reactors (HWRs), gas cooled reactors (GCRs) and liquid metal fast reactors (LMFRs).

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[12] A booklet entitled *Status of Small and Medium Sized Reactor Designs* has been published by the Agency and can be downloaded from: *http://www.iaea.org/NuclearPower/Downloads/Technology/files/SMR-booklet.pdf*. It is intended as a supplement to the Agency's Advanced Reactors Information System (ARIS), which is available at *http://aris.iaea.org*.

In Argentina, deployment of the CAREM reactor — a small, integral type, pressurized LWR design with all primary components located inside the reactor vessel and an electrical output of 150–300 MW(e) — started with the site excavation for the 27 MW(e) CAREM prototype plant in September 2011.

In Brazil, the conceptual design for the 70 MW(e) fixed bed nuclear reactor, which does not need on-site refuelling, has been developed.

Canada has developed and deployed globally the CANDU reactor series, which offers various power ratings. The Enhanced CANDU-6 Reactor is the new version that retains the basic features of the CANDU-6 design and has a gross electrical capacity of 740 MW(e).

China has developed 300 MW(e) and 600 MW(e) PWRs. Several units have already been deployed, and two units of the CNP-600 are under construction as of 2011. Pakistan has also deployed two CNP-300 units imported from China. Moreover, the China National Nuclear Corporation (CNNC) signed, in November 2011, an agreement with the municipal authorities of the city of Zhangzhou to construct two small modular nuclear power reactors.

Over the past couple of years, the Flexblue, a small offshore NPP which will be placed on the seabed and connected to power grids onshore, with an output of around 150 MW(e) has been under development in France.

In India, 21 HWRs of 220 MW(e), 540 MW(e) and 700 MW(e) are in operation or under construction. The 304 MW(e) Advanced Heavy Water Reactor (AHWR), which will use LEU and thorium mixed oxide (MOX) fuel and incorporate vertical pressure tubes and passive safety features, is in the basic design phase.

Japan is developing the Super-Safe, Small and Simple (4S) reactor — a small sodium cooled fast reactor which is designed to generate 10–50 MW(e) and which can be located in a sealed, cylindrical vault underground, with the building above the ground.

The Republic of Korea has developed the System-Integrated Modular Advanced Reactor (SMART) design, with a thermal capacity of 330 MW(th). It is intended for seawater desalination. A pilot plant design project was launched for comprehensive performance verification. The 100 MW(e) SMART is expected to obtain final standard design approval in the first quarter of 2012 prior to construction of a prototype plant.

In Pakistan, three SMRs are in operation, namely KANUPP-1, CHASNUPP-1 and CHASNUPP-2. Two CNP-300 reactors, imported from China for CHASNUPP units 3 and 4, are under construction.

In the Russian Federation, six light water cooled SMR designs are under development. Two units of the KLT-40S series are under construction and will be mounted on a barge and used for cogeneration of process heat and electricity. The Russian Federation has also developed the SVBR-100, a small fast reactor with a lead–bismuth eutectic (LBE) alloy as the coolant and a power output of 100 MW(e).

In Slovakia, two WWER-440 units based on Russian technology are under construction for the Mochovce units 3 and 4. The units are expected to commence operation in 2012 and 2013, respectively.

In the USA, four light water cooled integral PWRs are under development: mPower, NuScale, Holtec Inherently Safe Modular Reactor (HISMUR), and the Westinghouse SMR. The mPower is a twin-pack plant design consisting of two 185 MW(e) modules with an option to add additional twin packs based on the need. NuScale Power envisages an NPP that incorporates up to twelve self contained 45 MW(e) modules in the plant footprint and operates under natural circulation conditions in operating and post accident conditions. The Westinghouse SMR is a 225 MW(e) conceptual design incorporating passive safety systems and employs some of the passive safety philosophies and design features of the AP-1000 large LWR design. The HISMUR is a 145 MW(e) design that, like the NuScale modules, does not require pumps to circulate the coolant. The four concepts are expected to be submitted for design certification review with the US Nuclear Regulatory Commission between 2013 and 2015. The International Reactor Innovative and Secure (IRIS) project, which is now being carried out by an international consortium, aims to develop an integral PWR design with an electrical capacity of 335 MW(e). The Power Reactor Innovative Small Module (PRISM), a 311 MW(e) liquid metal cooled fast breeder reactor, has been developed and an application to the US Nuclear Regulatory Commission for design certification is being considered.

Several GCR designs in the SMR classification are being developed. China has built the HTR-10, an experimental pebble bed helium cooled HTR. As a follow-up plant, in March 2011, the Chinese Government approved the construction of the HTR pebble bed module (HTR-PM) consisting of two 250 MW(th) modules. In the USA, the 150 MW(e) gas turbine modular helium reactor (GT-MHR) is a conceptual design that has the potential to produce hydrogen by high temperature electrolysis or thermochemical water splitting. Finally, the Energy Multiplier Module (EM^2) design is an effort to utilize spent nuclear fuel without conventional reprocessing.

B.1.5. INPRO and GIF

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), which supports Member States in developing and deploying sustainable nuclear energy systems, welcomed three new members in 2011 — Egypt, Israel and Jordan — thereby increasing its membership to 35. The "INPRO Development Vision 2012–2017", elaborated in 2011, sets out the

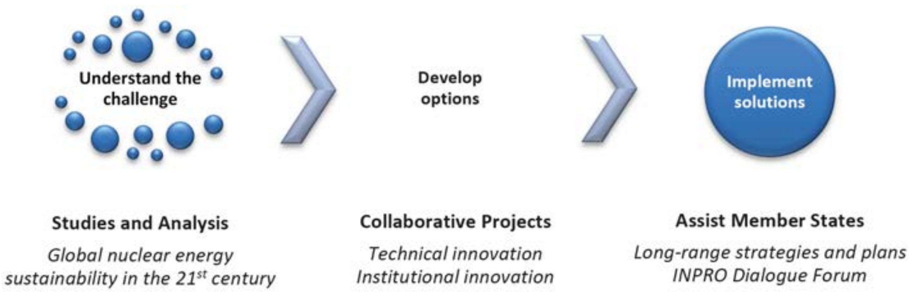

FIG. B-1. Global nuclear energy sustainability and INPRO's contribution.

strategic objective of working towards global nuclear energy system sustainability by modelling and analysing transition scenarios; promoting the required technical and institutional innovations; and supporting Member States in developing national long range nuclear energy strategies.[13]

In 2011, a new project was launched under the INPRO Dialogue Forum on Nuclear Energy Innovations to identify 'common user considerations', in particular of technology users for small and medium sized reactors (SMRs). Also in 2011, four Nuclear Energy System Assessments (NESAs) were under way in Belarus, Indonesia, Kazakhstan and Ukraine respectively, and the NESA Support Package developed by the Agency to support countries in their self-assessment was extended to include sample data and e-NESA software. The INPRO collaborative project Global Architecture of Innovative Nuclear Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) was concluded in 2011. It identified and quantified the benefit of transitioning to a globally sustainable nuclear energy system based on fast reactors and closed fuel cycles. A follow-up project, Synergetic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES), was initiated in 2011, with the objective of quantifying in detail the benefit of collaboration and synergies among countries in this transition process.

The Generation IV International Forum (GIF), through a system of contracts and agreements, coordinates research activities on six next generation nuclear energy systems selected in 2002 and described in *A Technology Roadmap for Generation IV Nuclear Energy Systems*: gas cooled fast reactors (GFRs), lead cooled fast reactors (LFRs), molten salt reactors (MSRs), sodium cooled fast reactors (SFRs), supercritical water cooled reactors (SCWRs) and very high

[13] This publication is available at *http://www.iaea.org/INPRO/files/INPRO_Development_Vision_(Final).pdf*.

temperature reactors (VHTRs). The six selected systems employ a variety of reactor, energy conversion and fuel cycle technologies. Their designs feature thermal and fast neutron spectra, closed and open fuel cycles and a wide range of reactor sizes, from very small to very large. Depending on their respective degrees of technical maturity, these systems are expected to become available for commercial introduction in the period between 2020 and 2030 or beyond. GIF currently has 13 members.[14]

The Agency and GIF cooperate in the areas of risk and safety, proliferation resistance and physical protection, economic evaluation modelling and methodologies as well as other topics such as SMRs, thorium use and fuel cycle implications. In 2011, the Fifth GIF/INPRO Interface Meeting reconfirmed the cooperation between GIF and INPRO, in particular on proliferation resistance evaluation methods and safety aspects of SFRs.

B.2. Fusion

The International Thermonuclear Experimental Reactor (ITER) project is an experimental project to demonstrate the scientific and technological feasibility and safety features of fusion energy for peaceful purposes. China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States participate in this international cooperation project. ITER is rapidly evolving, as reflected by both intensive on-site construction work and an increasing number of procurement packages for the various device and facility components. The progress made in the construction of the ITER site in 2011 includes the completion of the hot cell building, the excavation of the assembly hall, the concrete seismic pit base mat of the tokamak complex and the poloidal field coils winding facility. At the end of 2011, a total of 65 out of 126 procurement arrangements had already been signed, amounting to a total of over €3 billion and representing 74% of the total procurement value for the construction of ITER. The construction of major components (such as the vacuum vessel) and the production of crucial parts (such as the toroidal field superconductors) are under way in the States that are members of ITER. However, actions to minimize delays to the project schedule that were caused by the earthquake and tsunami in Japan in March 2011 need to be implemented.

Alongside ITER, international efforts have also been devoted to developing a roadmap for electricity production from magnetic confinement fusion (MCF). These activities have focused on the science and technology issues involved in

[14] Argentina, Brazil, Canada, China, Euratom, France, Japan, the Republic of Korea, South Africa, Switzerland, Russian Federation, UK and USA.

FIG. B-2. Hoisting superconducting correction coils to be used in ITER, Institute of Plasma Physics, Hefei, China.

setting up a fusion demonstration power plant (Demo) and the prerequisite research and development leading to Demo. A number of strategically important issues, which require further attention from the international community, have been identified:

— Assumptions used in fusion design codes — fusion reactor designs depend greatly on the physics and technology assumptions used at the design stage;
— Development of fusion materials — irradiation testing is a necessity, and may determine the critical path for developing structural and first wall materials for Demo;
— Development of blankets — tritium self-sufficiency is a requirement for fusion development beyond ITER, so breeding blankets will be required for essentially any next-step fusion nuclear facility, regardless of its intended purpose;
— Solutions for dealing with plasma exhaust — the heat and particle exhaust requirements for high duty-factor fusion devices go well beyond those of ITER;
— Requirements for the various next-step facility options — a plan is needed for closing the readiness gaps and meeting development needs for key fusion technologies in time to support the facility schedules.

These issues have strategic importance because the ways in which they are addressed will strongly influence the overall roadmap. As yet, there is no consensus on them among the international fusion community.

The 24th IAEA Fusion Energy Conference (FEC 2012) will be held in San Diego, California, USA, from 8 to 13 October 2012.

C. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

C.1. Accelerators

Accelerator based neutron sources, such as those in spallation neutron source facilities, have been used over the past few decades to complement research reactors. Currently, new spallation source facilities are under design and construction in China and in Sweden. In China, the groundbreaking ceremony for the China Spallation Neutron Source (CSNS), which will mainly consist of an H-linac and a proton rapid cycling synchrotron, took place on 20 October 2011. It is projected that CSNS will take seven years to complete, with the start of commissioning and of operation scheduled for 2016 and 2018 respectively. In Sweden, the European Spallation Source (ESS) is under development. Located in Lund, Sweden, and co-hosted with Denmark, ESS will be funded and operated by a partnership of 17 European countries. Currently, a technical design review is under way that will act as the blueprint for the construction of ESS, which is scheduled to start in 2013. ESS is expected to become operational in 2019 and to open up new opportunities for researchers within a large number of fields of research engaged in material analyses both at bulk levels and at the molecular level. These include: metallurgy; material sciences including nano materials and novel materials for energy research; archaeology; environmental engineering; food technology as well as chemical, biochemical and pharmaceutical sciences.

The March 2011 earthquake and tsunami in Japan heavily affected the Japan Proton Accelerator Research Complex (J-PARC). In 2011, the damage caused was being assessed and repaired, after which J-PARC is expected to resume operations.

New synchrotron facilities around the world are under construction to respond to increasing demand across the scientific community. MAX IV, a third generation synchrotron facility, is currently under construction in Lund, Sweden, and the commissioning of the completed facility is planned for 2014. Its design also includes an option for a free electron laser (FEL) in a second development stage. Also, the ALBA Synchrotron Light Facility in Spain has initiated beam commissioning during 2011 and expects to welcome its first users in early 2012.

The fourth generation FEL-based facilities — FERMI@Elettra (Italy), XFEL (Germany) and SwissFEL (Switzerland) — have all made significant progress. Commissioned in the spring of 2011, FERMI@Elettra is able to generate extremely short pulses (duration below 10^{-15} s) in the wavelength region of 10–100 nanometres (nm). The advent of femtosecond lasers has revolutionized many areas of science, from solid state physics to biology. This new research

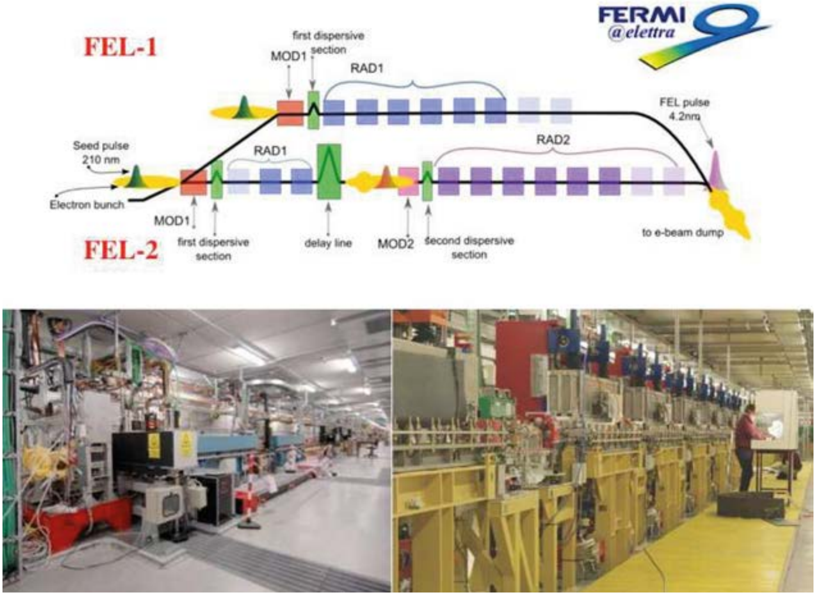

FIG. C-1. Schematic diagram of the FERMI free electron laser and inside views of the facilities (Photo credit: FERMI@Elettra).

frontier of ultra-fast vacuum ultraviolet (VUV) and X ray science is driving the development of novel sources for the generation of femtosecond pulses.

International collaboration plays a key role in the area of ion beam applications. One example of such collaboration is the EU-funded project CHARISMA (Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation/Restoration). CHARISMA combines the efforts of leading European museums (e.g. Museo del Prado, British Museum), research laboratories (e.g. French synchrotron facility Soleil) and university research groups to share access to advanced facilities, develop technologies for cultural heritage and provide training for young researchers. Several methods, including both traditional and advanced analytical techniques, are used to investigate the bulk, microscopic and surface properties of artefacts such as paintings, sculpture, metal work, ceramics, manuscripts and printed books, archaeological items and others.

C.2. Research Reactors

Over the past five years, a number of Member States have expanded their interest in nuclear energy or other nuclear technologies, including reactor produced medical and industrial isotopes and the application of nuclear technologies to the pursuit of advanced science. As a result, research reactors are becoming increasingly critical components in developing national or regional nuclear infrastructures.[15] Additionally, a trend towards the increased utilization and refurbishment of older research reactors has developed as the Agency works with Member States to improve the sustainability of facilities through international coalitions centred around one or more facilities.

At the end of 2011, there were 672 research reactor facilities around the world, of which 232 were operational, 13 had been temporarily shut down, 211 were permanently shut down, 213 were decommissioned and 3 were under construction.[16] In addition, 2 projects were planned and 5 had been cancelled. According to preliminary discussions held with the Agency, 14 Member States (detailed below) are considering building or planning new research reactors. For many of these Member States, this is an early step in a national programme to introduce nuclear power in parallel with other peaceful applications of nuclear technologies. Indeed, Azerbaijan, Saudi Arabia, Sudan and Tunisia are in the early stages of planning to build a research reactor as part of a larger national nuclear power programme. Construction has begun on a 5 MW multi-purpose research reactor in Jordan, while a project in Vietnam aims to set up a new research reactor in support of a national nuclear power programme. Established nuclear nations — including Argentina, Brazil, France, India, the Republic of Korea, the Netherlands, the Russian Federation and South Africa — are also building or planning new research reactors for specific experimental and commercial purposes.

As older research reactors are decommissioned and replaced by fewer, more multipurpose reactors, the number of operational research reactors and critical facilities is expected to drop to between 100 and 150 by 2020. Greater international cooperation will be required to ensure broad access to these facilities and their efficient use. Cooperative international networks are also proving to be helpful for upgrading existing facilities and developing new ones. Thus, in addition to the existing six research reactor coalitions in the Baltic, the Caribbean (which includes participation from Latin America), Central Africa, Central Asia, Eastern Europe and the Mediterranean, new coalitions and networks are envisaged — and necessary — to increase research reactor utilization and to make the remaining reactors truly viable. In this regard, the

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[15] Additional information can be found in the appropriate attachment to the *Nuclear Technology Review 2012* on the General Conference web site.

[16] According to the Agency's Research Reactor Database *(http://nucleus.iaea.org/RRDB/RR/)*.

Agency is also helping Member States to create a thematic network of research reactor facilities that can collaborate on common operation and maintenance activities, including developing a methodology for the implementation of the Agency's Operation and Maintenance Assessments for Research Reactors (OMARR) service. The main objectives of OMARR missions are to conduct comprehensive operation and maintenance peer reviews of research reactor facilities; to verify compliance with existing plant procedures; to suggest areas of improvement; and to facilitate mutual transfer of knowledge and experience, between mission experts and reactor personnel. The network will also support the sharing of information related to research reactor ageing management, collaborate on relevant coordinated research projects, share common challenges and develop joint activities.

Key issues and challenges faced by research reactors nowadays were extensively discussed at the International Conference on Research Reactors: Safe Management and Effective Utilization, held in Rabat, Morocco from 14 to 18 November 2011. This major Agency-organized event related to research reactors is held every four years. The latest conference concluded, inter alia, that research reactor coalitions provide the opportunity to offer products and services through multiple reactors that would not be possible with a single reactor and that, therefore, Member States should avail themselves of these coalitions wherever possible. Another important conclusion was that Member States planning a new research reactor should apply the Agency's 'Milestones approach,' and should ensure that the appropriate utilization plans and safety and regulatory infrastructure are in place. A diverse range of research reactors and ancillary facilities are currently offered by research reactor designers and providers. These were advised at the conference to adopt a 'safety by design' approach and to make every effort to maximize safety and efficiency parameters, including the lessons learned from the Fukushima Daiichi accident. Furthermore, on the basis of an Agency survey by questionnaire, it was noted in the conference that some action had been taken in response to the Fukushima Daiichi accident at two-thirds of the participating research reactor facilities. The conference recommended that research reactor operators actively re-examine their design basis and safety analysis to evaluate what, if any, changes and improvements should be made (as appropriate to the site and facility characteristics) so that facilities are able to sustain multiple severe external events.

The US-sponsored Global Threat Reduction Initiative (GTRI) continued throughout 2011 to carry out its mission to minimize the presence of high enriched uranium (HEU) in the civilian nuclear sector, including through the conversion of research reactor fuel and the targets used for radioisotope production from HEU to low enriched uranium (LEU). In 2009, the scope of GTRI was expanded from 129 research reactors to cover approximately

200 reactors around the world that operated with HEU fuel, and, by the end of 2011, 76 of these had been converted to LEU fuel or shut down before conversion. A recent example is Vietnam's research reactor which, on 30 November 2011, achieved criticality with 72 LEU fuel assemblies, completing the work begun in 2008 to convert the reactor core from HEU to LEU.

With Agency support, several Member States returned HEU research reactor fuel to its country of origin. Repatriation of fuel to the Russian Federation was very successful in 2010, with 2500 kg of spent fuel shipped back from Vinča, Serbia, to the Russian Federation. Repatriation efforts successfully continued in 2011, when much was accomplished in other Member States. A tripartite contract was signed with the Kharkov Institute (Ukraine) to return its last fresh HEU fuel stockpile (nearly 224 kg) to the Russian Federation before March 2012. China continued its efforts to convert the country's miniature neutron source reactors (MNSRs) from HEU to LEU, and is planning to work with the Member States that have purchased such reactors to help convert their reactors and to repatriate their HEU fuel. The Government of Mexico signed agreements in August and November 2011 to convert the country's TRIGA research reactor to LEU and repatriate the fuel to the USA. The first shipment took place in December 2011 and repatriation was completed by February 2012.

Conversion of medical isotope production processes from HEU to LEU also continued in 2011, with significant progress being achieved. Member States experienced severe molybdenum-99 (Mo-99) shortages from the end of 2007 until the third quarter 2010, due to the recurrent and unforeseen shutdown of aged reactors that were used for target irradiation and of a uranium target processing facility. As both reactors and production facilities returned to operation and new producers entered the relatively small community of suppliers, the shortages abated in 2011 and producers resumed conversion of Mo-99 targets from HEU to LEU. Australia reported progress in its efforts to increase the production of LEU-based Mo-99, and, in November 2011, Egypt confirmed successful irradiation and commissioning tests for the production of Mo-99 from LEU targets. South Africa continued its commercial production of Mo-99 made from LEU targets, while two major medical isotope producers (Belgium and the Netherlands) also began formulating and executing work plans to convert their commercial-scale production processes from HEU to LEU. Moreover, in 2011, the Agency completed a six-year long coordinated research project (CRP) that has assisted seven Member States (Chile, Egypt, Kazakhstan, Libya, Malaysia, Pakistan and Romania) in their efforts to assess the feasibility of nationally producing small-scale supplies of Mo-99 from fission-based LEU or by neutron activation methods. Finally, research into alternative Mo-99 production routes that are based on accelerator technologies has gained some momentum during 2011 and will probably continue in the years to come.

Advanced, very high density uranium–molybdenum fuels that are currently under development are required for the conversion of high flux and high performance research reactors. Although substantial progress in the development and qualification of uranium–molybdenum fuels was made in 2011, further efforts and testing, particularly in the context of irradiation and PIE programmes, are necessary in order to achieve the timely commercial availability of qualified very high density LEU fuels.

D. FOOD AND AGRICULTURE

D.1. Animal Production and Health

A resolution declaring the global eradication of rinderpest was adopted by the Conference of the Food and Agriculture Organization of the United Nations (FAO) in June 2011. The Agency celebrated this milestone during the 55th regular session of its General Conference in September 2011. Nuclear and nuclear-related techniques made an important contribution to the eradication of rinderpest with the development and implementation of diagnostic tests. In particular, the enzyme-linked immunosorbent assay (ELISA), a test capable of detecting specific rinderpest antibodies, as well as the virus, played an essential role in monitoring the vaccination campaign and disease status of animal herds, and in the surveillance of cattle populations to confirm freedom from the disease. It was based on previously developed radioisotope labelling of antibodies, using phosphorus-32 and sulphur-35 as markers for the secondary antibodies. Current ELISA systems use irradiated components (sera and antigens) in order to inactivate potentially infectious agents and to ensure the safety of the serological tests. These techniques are also relevant for addressing other transboundary animal diseases.

Traditional tracing of the migration paths of wild birds, using conventional extrinsic markers or satellite technologies (ringing or transmitter labelling) can give information only for the limited number of those wild birds that have been thus labelled. In 2011, it was demonstrated that stable isotope tracing technology can give information for each captured or dead bird. This is proving to be extremely useful in epidemiological investigations of avian influenza (tracing back to the source of an outbreak), as the disease can easily be transmitted via long distances in a relatively short period of time. There is increasing interest in using this technology to trace the origin of animal products intended for trade, independently from the statutory documentation required for the import and export of such products. Specifically, in the case of birds, the stable isotope profiles of feathers, claws and beaks may differ depending on their movement and nutrition patterns, and this allows for the determination of migration paths. A ‘proof of concept’ has been established in 2011, and research activities will be initiated in 2012 via a coordinated research project (CRP) in order to merge the data obtained from stable isotope profiling with data obtained from virus detection in environmental samples (faeces, natural water reservoirs) and genetic barcoding. This will enable simultaneous detection of the migration pathways, the bird species involved and their carrier status using more flexible sampling strategies.

In contrast to the promising results obtained with gamma irradiated vaccines for bacterial (*Brucella abortus*, *Listeria monocytogenes*), protozoal (*Trypanosoma anulata*, *Schistosoma japonicum*, *Plasmodium*, *Theileria parva*) and parasitic (*Dictiocaulus viviparous*, *Dictiocaulus filarial*) pathogens, the production of irradiated viral vaccines is still insufficiently examined. The results presented by scientists from the School of Molecular and Biomedical Science, University of Adelaide, Australia, during the meeting of experts held at the Agency's Headquarters in Vienna, Austria, in April 2011, have shown that gamma inactivated influenza vaccines can induce a much wider immune response than conventional (inactivated or attenuated) vaccines. This includes both T cell- and B cell-mediated immunity, whereas conventional vaccines mainly induce only B cell-mediated immunity. Moreover, these vaccines show cross-reactivity between different influenza subtypes, thereby extending the protection profile. It is expected that in the near future, further research on the feasibility of using irradiation to produce viral vaccines (for foot-and-mouth disease, Rift Valley fever, influenza and other viral pathogens) is likely to contribute significantly to improved strategies for the control of certain animal diseases.

In response to the Fukushima Daiichi accident in 2011, the Agency has been working to improve software aimed at sample collection, analysis, interpretation and decision making with regard to food contamination in the case of a nuclear or radiological emergency. The software has been designed as a referential integrity database, using unique numbers to link individual parameters in the sampling/reporting process. Thus, the concept is that the software will be able to generate numerous user-defined reports in real time. In addition, comprehensive information packages were developed for Member States to assist them in the implementation of remediation measures related to animal products and other agricultural products. This software, when completed, will serve as a platform to provide Member States with guidelines for upgrading their national contingency plans, as well as strengthening agricultural countermeasures following a nuclear accident.

D.2. Soil and water management

By 2050 the global population is expected to have reached 9 billion, representing an increase of approximately 2 billion over a 39-year period. This means an anticipated 50% increase in the demand for water. Agriculture currently uses 11% of the world's land surface for crop production, and accounts for 70% of all water withdrawn from aquifers, streams and lakes. On the basis of existing trends in the efficiency and yield gains of agricultural water use, it is projected that increased water use efficiency in agriculture, as well as improved practices for the protection of water quality in agricultural landscapes, will be required to meet this demand. Advances in nuclear technology can help to address these challenges.

D.2.1. Estimating water losses and their impacts on salinity under flood irrigation systems through the use of stable isotopes

Recent studies[17] have shown that measurements of the changes in isotopic signatures of water (deuterium and oxygen-18) at different stages during flood irrigation can be used to estimate water losses by evaporation and transpiration from crop lands for different soil types and irrigation rates. This approach is based on the principle that water molecules with lighter isotopes (hydrogen-1 and oxygen-16) leave the surface of the liquid more easily than the heavier ones (deuterium and oxygen-18) during evaporation, which causes the remaining water to be enriched with heavier isotopes. These studies have also demonstrated that the monitoring of deuterium, oxygen-18 and chloride concentrations in irrigation water, soil water and subsurface water over time can help in assessing the impacts of evaporation and transpiration on the development of soil salinity under flood irrigation systems. Results obtained from four study sites in Australia in 2011 indicate that transpiration is the dominant cause of water loss and therefore the largest contributor to salinity impact as measured by the increase in salt concentration in soils over a studied period of 14 days during flood irrigation. Salinity impacts caused by transpiration (0.4 to 2.6 t salt/ha) were 3 to 50 times greater than those caused by evaporation (0.01 to 0.3 t salt/ha) from irrigation and soil waters.

D.2.2. Area-wide soil moisture measurement using cosmic-ray neutrons

Information on area-wide soil moisture content is useful for estimating the water demand of various crops and therefore helps in the scheduling of large-scale irrigation, crop yield forecasts and climate change studies. Obtaining this measurement has been a challenge in the past as most of the devices available have a small range of soil moisture detection within 0.05–1 m in diameter from the devices. As a result, a large number of measurements are required, which can be both time-consuming and costly. The recent development of the cosmic-ray neutrons approach in Australia and the USA represents a breakthrough.[18] This

[17] VAN DEN AKKER, J., et al., Salinity effects from evaporation and transpiration under flood irrigation, J. Irrig. Drainage Eng. **137** (2011) 1–11.

[18] DESILETS, D., et al., Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays, Water Resour. Res. **46** (2010): W11505, doi:10.1029/2009WR008726.

FIG. D-1. COSMOS installation in a grazed pasture in Australia (photo courtesy of Dr. Chris Smith, Commonwealth Scientific and Industrial Research Organization (CSIRO): Land and Water, Canberra).

technique involves measuring fast neutrons generated naturally from cosmic rays and those produced from the soils resulting from the collision with water that is present at or near the land surface, thus allowing soil moisture status to be mapped over an area of approximately 700 m in diameter to a depth of 70 cm, which covers the rooting zones of most crops. As a result, this new instrument can complement point measurement devices, such as the soil moisture neutron probe (SMNP), to yield a reliable measure of soil moisture content at the level of the whole field. Moreover, the cosmic-ray neutron probe used in this technique, which is referred to as COSMOS (for "Cosmic-ray Soil Moisture Observing System"), is robust, can be easily carried out into the field, and integrates soil moisture data over an area 1 000 times larger than that covered by a SMNP. Thus, the COSMOS technique is less time-consuming and more economical for area-wide soil moisture measurements. It can also be used to evaluate the water distribution uniformity and efficiency of large-scale irrigation systems.

D.2.3. Plutonium (^{239}Pu and ^{240}Pu) — potential use of a fallout radionuclide for soil erosion and land degradation assessment

Recent studies[19, 20] have shown that the alpha-emitting plutonium isotopes plutonium-239 and plutonium-240 (with half-lives of 24110 years and 6561 years respectively) can be used to trace soil and sediment movement in water bodies. These isotopes are similar to caesium-137[21] in that they are fallout radionuclides originating from nuclear weapon testing and normally present in most soils, so there is no need to label the soil with these isotopes. However, the main advantage of plutonium-239 and plutonium-240 over caesium-137 lies in the longer half-lives of the plutonium isotopes compared to that of caesium-137 (30 years), which ensures the long-term availability of plutonium as a tracer of soil movement and deposition. Further studies are required to test these isotopes across a range of agro-ecological conditions.

D.3. Agricultural Remediation Practices and Technologies for Mitigating the Impacts of Radiation Contamination

It was after the Kyshtym accident in 1957 at the Mayak fuel reprocessing plant in the former Soviet Union that agricultural countermeasures against radiation contamination were first implemented on a large scale.[22] These practices were adapted, further developed and implemented in areas affected by the Chernobyl accident of 1986. New agricultural remedial actions based on an assessment of soil properties were suggested for arable soils and pastures (Fig. D-2). Effective countermeasures to minimize the contamination of animal products — such as the application of specific radionuclide binders to animal feed (e.g. ammonium ferric hexacyanoferrate to reduce radiocaesium absorption in the gut of grazing animals), the addition of stable analogues such as calcium to suppress radiostrontium absorption, clean feeding and live monitoring of animals

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[19] TIMS, S.G., et al., Plutonium as a tracer of soil and sediment movement in the Herbert River, Australia, Nucl. Instrum. Methods Section B **268** (2010) 1150–1154.

[20] HOO, W.T., et al. 2011, Using fallout plutonium as a probe for erosion assessment, J. Environ. Radiol. **102** (2011) 937–942.

[21] ZUPANC, V., MABIT, L., Nuclear techniques support to assess erosion and sedimentation processes: preliminary results of the use of ^{137}Cs as soil tracer in Sloveni, Dela **33** (2010) 21–36.

[22] ALEXAKHIN, R.M., "Remediation of areas contaminated after radiation accidents and incidents", Remediation of Contaminated Environments (VOIGT, G., FESENKO, S., Eds), Elsevier, Amsterdam (2009) 177–222, Ch. 4.

FIG. D-2. Application of soil based remedial options on a wet peat meadow in Yelne settlement, Rivno region, Ukraine (photo courtesy of Ukrainian Institute for Agricultural Radiology, Kyiv).

— were also developed and implemented at a large scale in areas affected by the accident.

As a result, a large amount of data on the effectiveness of agricultural countermeasures has been obtained and analysed, together with information on ancillary factors such as the required resources and costs. In addition, significant efforts have been made to identify many other factors which affect the potential application of various remediation options. Among these factors are different environmental conditions, radionuclide properties, land use of the contaminated areas and the remediation practices already deployed by local farmers and stakeholders. All of these factors can have a big impact on the effectiveness of agricultural countermeasures. These findings and lessons learned were recently critically reviewed by the Agency in the Chernobyl Forum report[23] and in some follow-up reviews by the Agency and other international organizations.[24]

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[23] *http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1239_web.pdf.*

[24] FESENKO, S.V., et al., An extended review of twenty years of countermeasures used in agriculture after the Chernobyl accident, Sci. Total. Environ. **383** (2007) 1–24.

FIG. D-3. Testing topsoil removal after using a soil hardener (Courtesy of Ministry of Agriculture, Forestry and Fisheries (MAFF)/Japan Atomic Energy Agency (JAEA)/National Agriculture and Food Research Organization (NARO), Japan).

The Fukushima Daiichi accident in Japan in 2011, which substantially affected a vast area of agricultural land, has presented new challenges. Although many of the options that were effectively used after the Kyshtym and Chernobyl accidents (soil based and agrochemical remedial measures) are being tested and partially implemented in the Fukushima region, the specific conditions of the affected area require new approaches to ensure food safety and sustainable agricultural production. In particular, new techniques were suggested for remediation of flooded rice paddy fields.

It is well known that traditional topsoil removal creates large volumes of disposed soil. The use of a soil hardener was tested in Japan as an approach for removing shallower layers of topsoil more easily (Fig. D-3). The advantage of this technology is that it allows faster and more efficient removal of radioactivity (greater than 80%) from the contaminated soil. The time required to carry out the remediation is just up to ten days per hectare (including time to let the topsoil harden after applying the hardener solution).

A second new technique being tested in Japan is specifically designed for flooded soils (i.e. rice paddies). Radioactivity levels in the soil are reduced by puddling the thin layer of topsoil under flooded conditions, draining the suspended soil (clay to light silt fraction), separating the sediments from the water, and finally disposing of the sediments only (Fig. D-4).

The efficiency of this technique in reducing the concentration of radiocaesium in the soil and the external dose rate, as observed in 2011 at a test

FIG. D-4. Draining suspended soil from paddies in Japan as a remediation option (courtesy of MAFF-NARO).

site in the Fukushima Prefecture, ranged between 15% and 70%, depending on the soil properties, i.e. clay and humus content. It should be noted that this technique generates up to 30 times less waste than the techniques based on traditional removal of 4 cm of the topsoil layer. Therefore, this method minimizes the deterioration of soil fertility.

D.4. Alternatives to gamma irradiation for the sterile insect technique[25]

Sterilization of insects as part of insect pest control programmes has traditionally used cobalt-60 or caesium-137 irradiators that produce gamma ray ionizing radiation. However, in response to the growing logistical complexities and difficulties of the transboundary shipment of radioisotopes, efforts were initiated to explore other options to sterilize insects for use in insect pest management programmes. Self-contained low-energy X ray irradiators, operating at medical institutes for blood irradiation, emit X rays only when the electrical power is turned on and the energy is in the range of a few hundred keV, requiring much less shielding than gamma irradiators.

Sterilization trials have been carried out to compare the cobalt-60 or X ray effects on insects. Information on residual fertility, adult emergence rates and

[25] Additional information is available in the appropriate attachment to the *Nuclear Technology Review 2012* on the General Conference web site.

mating competitiveness between gamma ray and X ray treated males competing for fertile females in field cages have so far revealed no significant differences. Machines incorporating all the modifications identified during the validation phase have already been provided to several Agency Member States. Nevertheless, several years will be needed to collect enough data to confirm whether this is really a viable alternative to sterilize insects under routine large scale operational conditions.

E. HUMAN HEALTH

E.1. Nutrition

E.1.1. Quality of growth during first 1000 days affects a person's health later in life

There is increasing recognition that appropriate nutrition during the first one thousand days of life from conception to two years of age can have a profound impact on a child's ability to grow and learn, and on the risk of developing chronic diseases, such as diabetes and heart disease, later in life.[26] Current standards for assessing a child's growth are primarily based on weight and length or height (WHO, Geneva, 2006[27] and 2011[28]). Health professionals can monitor a child's growth using charts showing normal growth in terms of weight and length or height for their age. While these anthropometric measurements are essential, there is a need for the definition of healthy growth to include measures of 'quality of growth'. Healthy growth is associated with development of lean tissue, while excess body fat is associated with increased risk of non-communicable diseases in adulthood. However, there are currently no standards for body composition in children.

For many countries in transition, improvements in child weight have taken place without commensurate improvements in height, with the result that if height is measured, children of normal weight are increasingly identified as short and relatively fat. This raises concern about the 'quality of growth'. Infants of similar weight or height can vary substantially in body composition. For example, Indian babies are small and thin at birth compared to European newborns, but they have more body fat and are at greater risk of non-communicable diseases

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[26] See the 1,000 Days web site: *http://www.thousanddays.org/*.

[27] WHO MULTICENTRE GROWTH REFERENCE STUDY GROUP, WHO Child Growth Standards: Length/height-for-age, weight-for-age, weight-for-length, weight-for height and body mass index-for-age: Methods and development, World Health Organization, Geneva (2006). See *http://www.who.int/childgrowth/standards/technical_report/en/*.

[28] WHO Anthro (version 3.2.2, January 2011): Software for assessing growth and development of the world's children. See *http://www.who.int/childgrowth/software/en/*.

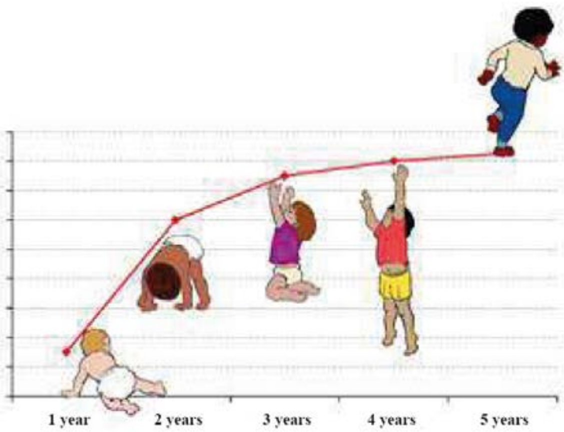

FIG. E-1. Image taken from WHO Child Growth Standards showing the development of a child's growth in the first five years of its life. These standards are based on data (height, weight, age) from approximately 8500 healthy breastfed infants and children from widely different ethnic backgrounds and cultural settings: Brazil, Ghana, India, Norway, Oman and the United States of America. (Copyright WHO, 2006).

during later adult life.[29] It is clear that although measurements of height and weight provide useful information, it is necessary to assess the components which contribute to body weight, in particular the relative proportions of fat-free mass (FFM) and fat mass (FM).

Nuclear techniques, such as stable isotope dilution, offer advantages in terms of sensitivity and specificity for monitoring relatively small changes in body composition, and can be used, for example, in the evaluation of nutrition intervention programmes designed to combat the double burden of nutrition-related diseases, where acute malnutrition coexists with obesity and related chronic diseases.[30]

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[29] YAJNIK, C.S., et al., Neonatal anthropometry: The thin–fat Indian baby. The Pune Maternal Nutrition Study, Int. J. Obes. Relat. Metab. Disord. **27** 2 (2003) 173–180.
WORLD HEALTH ORGANIZATION, Appropriate body-mass index for Asian populations and its implications for policy and intervention strategies, Lancet **363** (2004) 157–163.

[30] CORVALAN, C., et al., Impact of growth patterns and early diet on obesity and cardiovascular risk factors in young children from developing countries, Proc. Nutr. Soc. **68** 3 (2009) 327–337.
UAUY, R., KAIN, J., CORVALAN, C., How can the developmental origins of health and disease (DOHaD) hypothesis contribute to improving health in developing countries? Am. J. Clin. Nutr. **94** 6 (2011) 1759S–1764S.

In Chile, stable isotope techniques have been used to evaluate national intervention programmes aimed at reducing the prevalence of obesity in preschool children. The prevalence of obesity in children (aged 2–3 years) attending national day care centres has been reduced from 10.4% to 8.4%. In recognition of the need to intervene earlier, a new programme has been established in 2011, in which stable isotope techniques will be used to validate a Motor Development and Physical Activity Promotion Programme for children aged 6–24 months.

The Agency, in close collaboration with international experts, prepared guidelines in 2011 for the standardization of techniques used to assess body composition in infants and young children.[31] These guidelines provide an essential first step towards setting standards for evaluating the growth and nutrition of infants and young children using nuclear and non-nuclear body composition assessment techniques.

E.2. Advances in Radiation Medicine for Cancer Treatment

E.2.1. Modern radiotherapy calls for quality data management

Over the past decade, radiation oncology technology has become increasingly more complex and computerized. A number of treatment aids and accessories, which are manually inserted into radiation beams in order to deliberately alter their fluence (intensity) and, in so doing, optimize the treatment, are now also available as digital devices. For instance, the radiation beam shape is currently often defined by multi-leaf collimators, which not only shape the field, but can also move within the field during treatment. It is no longer possible to manually programme and deliver such complex treatments because of the number of parameters that define the treatment of each radiotherapy patient. Electronic patient records are therefore necessary. Embedded in these records are not only the patient’s administrative details, their radiation prescription and radiation dose records, but also the details of all the parameters that define each of their radiation fields. Hierarchical password-controlled security measures are necessary to ensure that these records remain uncorrupted and contain the correct information to ensure that treatment is delivered reproducibly every day over a course of radiotherapy, which usually takes a few weeks.

[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Body Composition Assessment from Birth to Two Years of Age (in press).

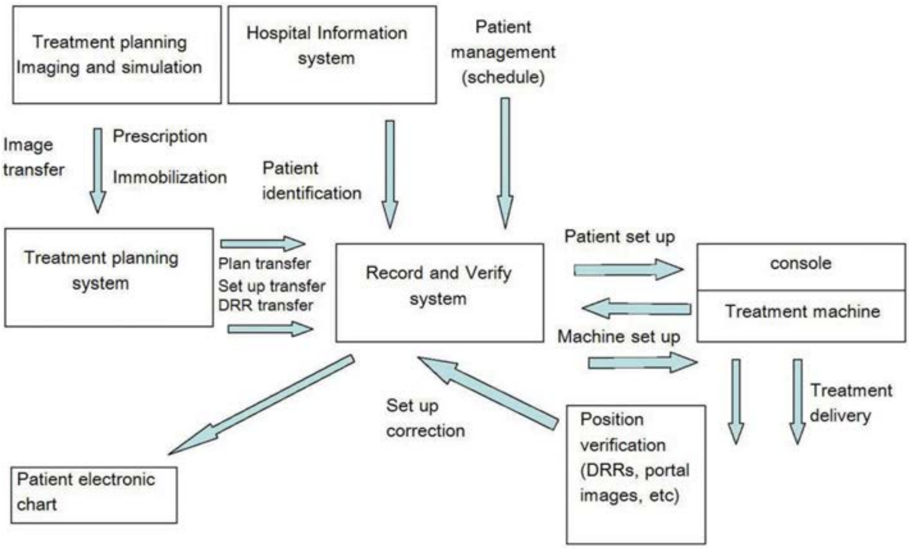

FIG. E-2. Illustration of typical data exchanges between the RVS and other pieces of equipment in a modern radiotherapy department. Different manufacturers may propose different solutions, offering a greater or lesser degree of integration of the various components.

A ‘record and verify system’ (RVS) is a type of radiotherapy patient database management system that is central to most modern digital radiotherapy departments. Such systems link all the radiotherapy imaging, treatment planning and treatment delivery equipment together (see Fig. E-2). Radiotherapy equipment is often supplied by different vendors, and therefore adherence to common digital communication protocols is necessary to ensure data transfer integrity across all interfaces. Traditionally, all radiotherapy equipment has been subject to rigorous quality control procedures to ensure that all modalities perform adequately. However, international guidelines on the acceptance testing and systematic quality assurance of RVSs have been lacking. In order to promote safe and effective patient treatment, the Agency has produced guidelines in 2011 for sound quality management of RVSs, which have been endorsed by all the major suppliers of radiotherapy equipment.

E.2.2. Current trends in cancer management with radiotherapy

The accurate targeting of tumours with maximal sparing of normal tissues has been the foremost goal of radiotherapy practice. Over the last two decades, the ability to achieve this goal has improved greatly. This achievement has been made possible by advances in imaging technology, specifically the development of computerized tomography (CT), magnetic resonance imaging (MRI), positron-emission tomography (PET) and fusion PET/CT.[32]

Developments in imaging technology coupled with advances in computer technology have fundamentally changed the processes of tumour targeting and radiation therapy planning. The ability to display anatomical information in an infinite selection of views has led to the emergence of three-dimensional conformal radiotherapy (3D-CRT); a modality in which the volume treated conforms closely to the shape of the tumour volume.

Intensity modulated radiation therapy (IMRT) assigns non-uniform intensities to a tiny subdivision of beams called beamlets. The ability to optimally manipulate the intensities of individual rays within each beam leads to greatly increased control over the overall radiation fluence (i.e. the total number of photons/particles crossing over a given volume per unit time). This in turn allows for the custom design of optimal dose distributions. Improved dose-distributions often lead to improved tumour control and reduced toxicity in normal tissue.[33]

Image-guided Radiation Therapy (IGRT) can be defined as a technology aimed to increase the precision of radiotherapy, by the frequent imaging of the target and/or healthy tissues just before treatment and thereafter adapting treatment based on these images. There are several image-guidance options available: non-integrated CT scans, integrated X ray (kv) imaging, active implanted markers, ultrasound, single-slice CT, conventional CT or integrated cone-beam CT.[34]

Helical tomotherapy (HT) is a modality of radiation therapy in which the radiation is delivered slice-by-slice (hence the use of the Greek prefix tomo-, which means “slice”). This method of delivery differs from other forms of external beam radiation therapy in which the entire tumour volume is irradiated at one time.[35] The main advantage of this method is the relatively short overall irradiation time.

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[32] VIKRAM, B., COLEMAN, C.N., DEYE, J.A., Current status and future potential of advanced technologies in radiation oncology: Challenges and resources, Oncol. **23** 3 (2009) 279.

[33] GALVIN, J.M., et al., Implementing IMRT in clinical practice: A Joint Document of the American Society for Therapeutic Radiology and Oncology and the American Association of Physicists in Medicine, Int. J. Radiat. Oncol. Biol. Phys. **58** 5 (2004) 1616–34.

[34] VAN HERK, M., Different styles of image guided radiotherapy, Sem. Radiat. Oncol. **17** 4 (2007) 258–267.

[35] ROCK MACKIE, T., et al., Tomotherapy; A new concept for the delivery of dynamic conformal radiotherapy, Med. Phys. **20** 6 (1993) 1709¬1719.

Volumetric modulated arc therapy (VMAT) is a technique that delivers a precisely sculptured 3D dose distribution with a single 360-degree rotation of the linear accelerator gantry.[36] It is made possible by a treatment planning algorithm that simultaneously changes three parameters during treatment: rotation speed of the gantry, shape of the treatment aperture using the movement of multileaf collimator leaves and delivery dose rate.

Stereotactic radiotherapy (SRT), (also called "radiosurgery" although there is no surgery involved) consists of the delivery of a relatively high dose of radiation to a small volume using a precise stereotactic localization technique. The stereotactic component of the technique refers to immobilization or fixation of the patient with a rigid head frame system that establishes a patient-specific coordinate system for the entire treatment process.[37] This modality is usually applied in the treatment of intra-cranial tumours. After placement of the head frame, typically by use of four pins that penetrate the scalp and impinge the outer table of the skull, an imaging study (CT, MRI) is performed to localize the target volume relative to the head frame coordinates.

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

Brachytherapy (BT) is the administration of radiation therapy by placing radioactive sources adjacent to or into tumours or body cavities. With this mode of therapy, a high radiation dose can be delivered locally to the tumour with rapid dose fall-off in the surrounding normal tissues. In the past, brachytherapy was carried out mostly with radium or radon sources. Currently, use of artificially produced radionuclides such as caesium-137, iridium-192, gold-198, iodine-125 and palladium-103 is rapidly increasing.

Respiratory gated radiotherapy. Radiation oncologists face particular problems in treating parts of the body where organs and tumours may move during treatment. Movement of the target due to respiration or for any other reason during treatment increases the risk of missing the targeted area or under-dosing the area. As the delivery of the radiation dose becomes more and more precise, movements of organs and tumour become a significant influence on the accuracy of the dose delivery. This is particularly dramatic for tumours located in the chest, since they move during breathing. Movement is not only an issue with

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[36] OTTO, K., Volumetric modulated arc therapy: IMRT in a single gantry arc, Med. Phys. **35** 1 (2008) 310.

[37] BOURLAND, J.D., "Stereotactic radiosurgery", Clinical Radiation Oncology, 2nd edn (GUNDERSON, L.L., TEPPER, J., Eds), Elsevier Churchill, Livingstone (2007) 151 Ch. 6.

tumours located in the chest; tumours in the larynx, abdomen (liver), prostate, and bladder and in the pelvis in general also move during and between treatment applications.

PET in radiotherapy treatment planning. Recent years have seen an increasing trend in the use of PET and PET/CT imaging in oncology. Along with diagnosis, staging, relapse detection and follow-up, one of the main applications of PET/CT is the assessment of treatment response and treatment planning. PET provides molecular information about the tumour microenvironment ("functional imaging") in addition to anatomical imaging. Therefore, it is highly beneficial to integrate PET data into radiotherapy treatment planning. The use of functional imaging to better delineate the treatment target is a good example of individualized treatment. In fact, instead of using a previously established field or set of fields, the radiation dose is shaped on the tumour for each individual patient.[38]

Particle therapy: proton beam and heavy ions. There is an increasing use of particle therapy in the field of radiation oncology with increasing focus on the application of proton beam therapy. According to data from the Particle Therapy Co-Operative Group, as of March 2010 there are 30 proton therapy centres in operation worldwide, and more than 67 000 patients have been treated with this modality. The number of operating proton centres is projected to double in the near future.

Recent technological developments in radiation oncology have resulted in better dose distributions and reduced toxicity in selected tumour sites which may in turn lead to potentially higher chances of local tumour control and improved cure rates. This is one of the reasons for these treatments to have gained in popularity among radiation oncologists and hospital administrators. However, increased revenues of the IMRT and other new technologies may lead to their over-utilization. The clinical scientific evidence regarding local tumour control and overall cancer survival for most tumour sites are generally inconclusive at this time.

The IAEA, through its Programme of Action for Cancer Therapy, and in cooperation with its partners like the World Health Organization continues to deliver comprehensive cancer control to Member States. In 2011, eight integrated missions of PACT (imPACT) took place to assess the national capacity and needs in various components of the comprehensive cancer control in Algeria, Bolivia, Colombia, Lesotho, Nigeria, Paraguay, the Philippines and Uganda. All but one of the eight PMDS sites (Albania, Ghana, Nicaragua, Mongolia, Sri Lanka,

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[38] CHITI, A., KRIENKO, M., GREGOIRE, V., Clinical use of PET-CT data for radiotherapy planning; What are we looking for? Radiat. Oncol. 96 (2010) 277–279.

United Republic of Tanzania, Vietnam and Yemen) have received a follow-up mission by PACT and its partners to follow up on the recommendations for a comprehensive cancer control approach through partnerships.

E.2.3. Diagnostic imaging and treatment of breast cancer[39]

Although the incidence of breast cancer (expressed as age standardized rate) is almost three times higher in developed than in developing countries, this is the most common female cancer regardless of a country's socioeconomic level. Mortality is growing, especially in those regions of the world without early detection programmes. Age, family history and genetics, late first pregnancy, and obesity are well-established risk factors for breast cancer. Imaging plays a crucial role in breast cancer screening, and in classifying and defining the extent of breast tumours.

Most breast cancers are detected by X ray mammography, usually as part of nationwide screening programmes. Ultrasound (US) examination is routinely used as an essential complement to physical examination and mammography in the evaluation of suspicious/equivocal breast masses. Ultrasound has also become the modality of choice for guiding percutaneous interventional procedures on breast masses, from core needle biopsy to ablation. Magnetic resonance imaging (MRI) with contrast agent plays an important role in identifying mammographically equivocal breast masses as malignant or benign, as well as in defining the local extent of malignant disease.

Apart from radiological imaging (mammography, US, MRI), nuclear medicine imaging techniques are playing an increasing complementary role in the diagnostic characterization of breast lesions, especially when dedicated breast-imaging devices are employed, both for conventional scintimammography and above all for positron emission tomography (PET). Radionuclide procedures are essential for radio-guided surgery in patients with breast cancer, either as radio-guided occult lesion localization (ROLL) or as radioguided sentinel lymph node biopsy in the phase of primary treatment. Whole-body PET is also of paramount importance for systemic staging, for restaging after neoadjuvant therapy of locally advanced breast cancer, and for assessing the efficacy of anti-tumour therapy.

Breast cancer is usually treated combining surgery, radiotherapy, chemotherapy, and hormonal therapy. Treatment selection is based on clinical and pathological prognosis factors, which include the stage of the disease at

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[39] Additional information is available in the appropriate attachment to the *Nuclear Technology Review 2012* on the General Conference web site.

presentation, histology and differentiation of the tumour, age and menopausal status, the presence or absence of estrogenic-progesterone receptors, and overexpression of human epidermal growth factor type 2 receptor (*HER2/neu*).

In early breast cancer postoperative radiotherapy improves both local tumour control and survival. On the other hand, breast cancer survivors have higher probability to develop long-term complications. Cardiac toxicity manifestations such as coronary artery disease, pericarditis, cardiomyopathy, valvular disease, conduction abnormalities, etc., usually occur ten or more years later after the treatment. During the past decade, advances in radiotherapy technology contributed to decreasing toxicity of breast cancer treatment. Use of three-dimensional conformal radiotherapy (3-D CRT) allows applying necessary radiation dose to the volume which conforms closely to the tumour volume. At the same time, normal organs (e.g. heart, lung) can be spared.

Intensity modulated radiation therapy (IMRT) is a sophisticated type of three-dimensional conformal radiotherapy that assigns non-uniform intensities to a tiny subdivision of beams called beamlets. The ability to optimally manipulate the intensities of individual rays within each beam (also called "dose-painting") allows for beneficial dose distribution: high dose to the tumour and low dose to normal organs (heart, lung, skin, etc.).

Another high-precision advanced radiotherapy technique, which is successfully applied in breast cancer radiotherapy, addresses the problem of target movement due to normal respiration. This technique takes into account the fourth dimension, movement in time, and that is why it can be referred also as "four-dimensional conformal radiotherapy (4-D CRT)". Such computer-driven respiratory gated radiotherapy enables analysis of chest movements and triggers the treatment beam synchronized with the respiratory cycle. A specific respiratory phase (inspiration or expiration) can be chosen for irradiation. Therefore, the target will always be encompassed by the radiation beam while avoiding the excessive exposure of critical organs due to safety margin reduction.[40]

For accelerated partial breast irradiation (APBI) — where the tumour bed is treated with a high dose per fraction and the entire local postoperative course is completed in five days or less-high dose rate (HDR) brachytherapy (BT) can be used along with external beam radiotherapy. Brachytherapy is the administration of radiation therapy by placing radioactive sources adjacent to or into tumours/tumour bed or body cavities. With this mode of therapy, a high radiation

[40] GIKAS, S.M., YORKE, E., Deep inspiration breath hold and respiratory gating strategies for reducing organ motion in radiation treatment, Sem. Radiat. Oncol. **14** 1 (2004) 6575.

dose can be delivered locally to the tumour with rapid dose fall-off in the surrounding normal tissues. In case of breast cancer either interstitial multicatheter BT or intracavitary BT using an inflatable balloon can be performed.

Treatment of locally advanced breast cancer (advanced tumour within the breast >5 cm or invading skin or chest wall, or any tumour size in breast with metastases to regional nodes) still represents a major challenge[41, 42]. With operable disease (when the tumour and nodes are not fixed and there are no distant metastases, e.g. bone, brain, liver, etc), treatment consists of a combination of surgery, chemotherapy and/or hormonal therapy, and radiation therapy. The benefit of each modality has been demonstrated in large randomized trials[43, 44, 45, 46]. Even when adjuvant chemotherapy is given, a substantial risk of loco-regional recurrence exists after adequate surgery. Risk factors for loco-regional failure include age, tumour size, pre-menopausal status, number of positive lymph nodes and use of systemic therapy. The time to loco-regional

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[41] SINGLETARY, S.E., et al., Revision of the Amercian Joint Committee on Cancer Staging System for breast cancer, J. Clin. Oncol. **20** (17) (2002) 3628–3636.

[42] GREENE, F.L., et al. (Eds), AJCC Cancer Staging Manual, Sixth Edition, Springer-Verlag, New York (2002).

[43] TAGHIAN, A.G., et al., Low locoregional recurrence rate among node-negative breast cancer patients with tumors 5 cm or larger treated by mastectomy, with or without adjuvant systemic therapy and without radiotherapy: results from five national surgical adjuvant breast and bowel project randomized clinical trials, J. Clin. Oncol. **24** (24) (2006) 3927–3932.

[44] TAGHIAN, A., et al., Patterns of loco regional failure in patients with operable breast cancer treated by mastectomy and adjuvant chemotherapy with or without tamoxifen and without radiotherapy: results from five national Surgical Adjuvant breast cancer and Bowel Project randomized clinical trials, J. Clin. Oncol. **22** (21) (2004) 4247–4254.

[45] NIELSEN, H.M., OVERGAARD, M., GRAU, C., JENSON, A.R., OVERGAARD, J., Study of failure pattern among high-risk breast cancer patients with or without postmastectomy radiotherapy in addition to adjuvant systemic therapy: long-term results from the Danish Breast Cancer Cooperative Group DBCG 82 b and c randomized studies, J. Clin. Oncol. **24** (15) (2006) 2268–2275.

[46] RECHT, A., et al., Locoregional failure 10 years after mastectomy and adjuvant chemotherapy with or without tamoxifen without irradiation: Experience of the Eastern Cooperative Oncology Group, J. Clin. Oncol. **17** (6) (1999) 1689–1700.

recurrence has been reported to be as short as 3 to 12 months[47], but most loco regional recurrences occur within 3 years.

The IAEA is conducting a study under coordinated research programme (CRP E33025) on breast cancer patients who underwent mastectomy and require postoperative radiotherapy. This clinical trial compares two different radiotherapy field setups, in order to investigate if irradiation of the supraclavicular area can be avoided or not. Since IAEA clinical research objectives are based on the potential advantage of resource sparing strategies, the fractionation used in this study shortens the overall duration of radiotherapy to 3 weeks, compared to 5 weeks of conventional fractionation. This approach would permit busy radiotherapy departments with long waiting lists to use evidence-based protocols with shorter or simpler treatments.

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[47] ADENIPEKUN, A., CAMPBELL, O.B., OYESEGUN, A.R., ELUMELU, T.N., Radiotherapy of early breast cancer in Ibadan: Outcome of chest wall irradiation alone in clinically nodes free axilla, Afr. J. Med. Medical Sci. 2002; **31** (4) (2002) 345–7.

F. ENVIRONMENT

F.1. Rapid Radioanalytical Methods can Make a Difference in Assessing Radioactive Pollution in Emergency Situations

The Fukushima Daiichi accident demonstrated that a huge number of environmental samples may need to be analysed in a very short lapse of time, stretching greatly the human, material and logistical resources of analytical laboratories. As shown by the very large amount of effectively ‘real-time’ data reported on a regular basis by the Japanese authorities, in such situations it is critical to expedite the analytical throughput time and optimize analytical strategies so as to comply with quantitative regulatory limits and accepted quality criteria.

Whether in the case of nuclear emergencies, accidental releases from various nuclear facilities or malicious acts involving a radiological attack, the promptness with which an assessment of the environmental releases and contamination is made available to the authorities can have dramatic effects on the safety of the individuals and populations at risk. Immediately after an incident resulting in potential environmental releases, radiation monitoring through dose rate measurements and rapid screening methods, such as aerosol and gas radioactivity monitoring and radiation mapping, are the common methods recommended to be used. In many types of accidental situations, environmental radioactive contamination can be rapidly evaluated by the use of field gamma ray spectrometry, involving in situ screening of deposition, soil contamination mapping using mobile units, as well as aerial and underwater gamma surveys. A wide area can thus be screened in a relatively short time, the extent and scale of contamination can be defined and sampling strategies can be optimized.

At a later stage of a radiological event, more accurate and precise analyses of samples collected according to validated protocols should be carried out in order to assess the radiation exposure more accurately. A comprehensive dose reconstruction requires the analysis of the full spectrum of radionuclides, including gaseous, particulate and liquid forms, starting from the very early stages of a release. Gross and spectrometric alpha, beta and gamma measurements are commonly carried out on bulk or radiochemically processed samples. The Fukushima Daiichi accident highlighted the importance of having analytical laboratories that are able to cope with a potentially large increase in their workload. Rapid methods allow the time required for analysis to be reduced from days or weeks to hours or days. The validation and implementation of such methods is necessary above all for radionuclides which pose significant radiological concern in all potentially affected environmental media, as well as, very importantly, for food and animal feed.

The use of well characterized and validated sampling and analytical procedures is especially important in the case of transboundary environmental assessments, in which several laboratories or laboratory networks are involved, and where the comparability of measurements is a major issue. The Agency supports Member States' laboratories and laboratory networks through training, coordinated research projects (CRPs), provision of reference materials for a wide range of contaminants, collaborative development and implementation of analytical techniques, and the organization of proficiency tests and interlaboratory comparisons. The Agency-coordinated ALMERA network, a worldwide network of analytical laboratories for the measurement of environmental radioactivity, consists of laboratories nominated by Member States and is able to provide reliable and timely analysis of environmental samples in the event of an accidental or intentional release of radioactivity.

ALMERA is engaged in the collaborative validation of rapid methods and will further focus its efforts on radionuclides and samples of interest for emergency situations. The 2011 proficiency test organized for the ALMERA network focused on alpha, beta and gamma emitters in soil and water samples. A short 3-day deadline after receipt of the samples was set for the rapid reporting of gamma emitting radionuclides to test the laboratories' analytical performance under time constraints. In future, additional reference materials and proficiency tests with short reporting deadlines will be developed by the Agency and by laboratories in the ALMERA network in order to comprehensively cover all the requirements posed by emergency situations. During 2012, attention will be focused on the quality and comparability of analyses of aerosol samples.

The Fukushima Daiichi accident also showed that devolving the analytical burden to laboratories within a well-coordinated network and the deployment of mobile laboratories are useful additional solutions and require advance planning. Equally important for supporting timely decision making is a fast and reliable data validation and reporting mechanism. Modern mobile communication technology brings to the field the combined strength of computerized relational databases, geographical information systems, multimedia documenting, on-line access to procedures and operational assistance supporting data traceability and quality. The integration of remote sensing with hydro-meteorological observations and modelling is critical for providing rapid guidance in adjusting the monitoring strategy, as well as further on when preparing the authorities' response. As compared to the more common aerial and terrestrial in situ gamma spectrometry, an area obviously requiring technological development is in situ underwater monitoring through stationary and mobile high resolution gamma

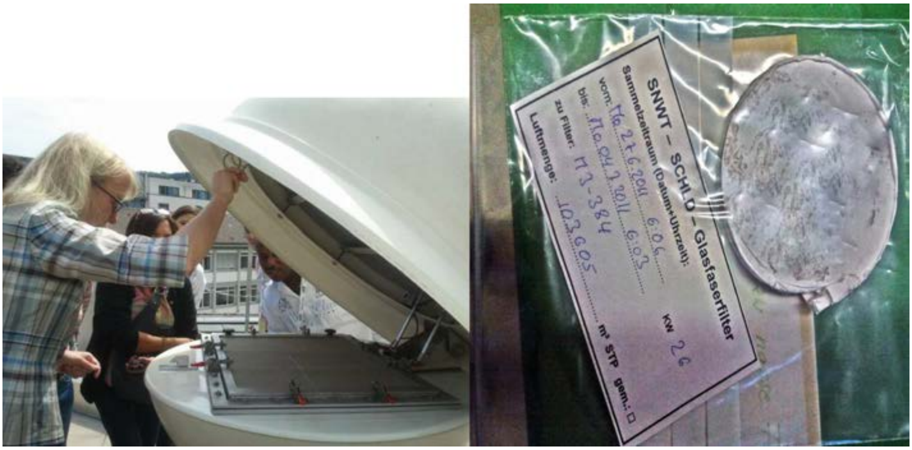

FIG. F-1. Large volume aerosol collector operated by the Federal Office for Radiation Protection in Salzgitter, Germany, and aerosol filter compacted for immediate gamma spectrometric counting - being demonstrated to participants in the Agency's Interregional Advanced Training Course on Marine Radioactivity: Analytical Techniques and Quality Management hosted by the Karlsruhe Institute of Technology in 2011.

spectrometry of the coastal marine environment, which allows a reconstruction of liquid radioactive releases and rapid screening of water and sediment contamination.

G. WATER RESOURCES

The demand for water in agriculture, energy, industry and for urban uses continues to grow worldwide. Along with an increasing concern about the impact of predicted climate change on the hydrological cycle, this growing demand is bringing about major changes in the allocation and management of water resources. In some places, the situation has escalated into conflict due to difficulties in providing access to safe water, as highlighted in the World Water Day 2011 report [48], which addressed the problem of water access in the context of urban development. Since most surface waters have been allocated and/or are becoming polluted, groundwater is expected to play an even greater role in the near future and to supply much of the world's fresh water. Unfortunately, most countries lack the required knowledge of their groundwater resources to ensure an adequate supply of water.

In order to adopt appropriate policies that will facilitate the sharing of limited resources, access to sound and comprehensive information on the availability and condition of existing water resources is required. Isotope methods provide unique information that can be used to assess and map groundwater resources rapidly and effectively. Isotope techniques and related geochemical tools, coupled with newer mapping developments through the use of geographical information systems (GISs) and geostatistical methods, are helping water experts and managers to better delineate, quantify and visualize the geometry, volume and properties of aquifers and groundwater bodies. Maps identifying water bodies more resilient to climate change or areas of active recharge are critical to ensure access to water on a long-term basis.

G.1. Trends in access to stable isotope data

In 2011, the use of low cost and easy-to-operate devices for the analysis of the stable isotopes in water (oxygen-18 and deuterium), based on laser spectroscopy, became standard procedure for research groups worldwide. Due to this innovation, many groups in developed and developing countries have become autonomous in their ability to analyse stable isotopes for hydrological studies, avoiding delays in obtaining analytical results from high-profile laboratories and benefitting from lower costs. For example, studies aiming at assessing groundwater resources in Santa Elena peninsula in Ecuador

[48] See *http://www.unwater.org/downloads/World_Water_Day_2011_Final_Report_Web.pdf*.

FIG. G-1. Better access to groundwater resources in communities in coastal Ecuador is one of the results of improved scientific understanding achieved largely thanks to data obtained from stable isotope analysers (courtesy of ESPOL, Guayaquil, Ecuador).

(see Fig. G-1) are being conducted in a more efficient manner due to the availability of such an analyser. Over the next year, the development of new analysers for carbon-13 and nitrogen-15 based on the same technology is expected to accelerate, thereby facilitating the use of these isotopes in the study of groundwater and surface water.

G.2. Groundwater dating

As opposed to analytical equipment for stable isotopes, many developing Member States lack the necessary analytical equipment for measuring the low activity levels of radionuclides that are often used in groundwater dating, which is important for assessing sustainability, vulnerability to pollution and replenishment rates. Environmental radionuclides, such as tritium or carbon-14, have been commonly used to gain this knowledge. In recent years, a number of analytical developments have improved the analysis of these isotopes (for example, tritium analysis using the helium in-growth methods and mass spectrometry), but the number of facilities remains limited. Similarly, the tritium/helium-3 method for dating recently recharged groundwater bodies is now applied more frequently, but access to analytical facilities able to support this technique is also limited.

The use of isotopes of noble gases to date groundwater in several age ranges has increased significantly in the last couple of years, and their use is continuing to increase, as is research in this area. For example, institutions such as the Argonne National Laboratory, USA, and Heidelberg University, Germany, are developing atom trap trace analysis (ATTA) techniques, which are opening up new possibilities for the dating of groundwater using noble gas isotopes. In the case of recently recharged groundwater (up to 100 years), krypton-85 is being used. For groundwater recharge up to 2000 years ago, argon-39 has also been successfully applied. In the case of large aquifers in sedimentary basins, such as the Nubian Sandstone Aquifer System (NSAS) in northern Africa and the Guarani Aquifer System in South America, where the age of groundwater in these deep aquifers can reach up to 1 million years, long-lived radionuclides such as krypton-81[49] are increasingly being used, improving flow and transport groundwater models. Isotope hydrology offers the potential to obtain the required information on the available quantities of water, as well as water quality and expected evolution. The Agency continues to play a key role in reviewing and assessing these new tools and methodologies and in providing access and knowledge transfer to interested Member States.

[49] See *http://www.nytimes.com/2011/11/22/science/rare-krypton-81-isotope-helps-track-water-in-ancient-nubian-aquifer.html?src=dayp.*

H. RADIOISOTOPE PRODUCTION AND RADIATION TECHNOLOGY

H.1. Radioisotopes and radiopharmaceuticals

H.1.1. Recent developments in generator produced PET radionuclides

Progress in nuclear imaging has always been closely linked to the production of new radionuclides with novel physical and chemical properties. Generator-produced radionuclides for use in PET are becoming more accessible because they can be produced in hospitals without an on-site cyclotron. Currently, gallium-68 (^{68}Ga) is available from commercial ^{68}Ge/^{68}Ga generators and is widely used in PET imaging. This is an important technical development as ^{68}Ga, being chemically similar to lutetium-177 and yttrium-90 (two radionuclides increasingly used for therapy of certain cancers) could be tagged to biologically active peptides such as octreotide using the established chemical route via DOTA linkage and used for delineation of neuroendocrine tumours through diagnostic scans, before therapy. Based on the success with ^{68}Ga-DOTATATE, the potential of novel ^{68}Ga labelled peptides for imaging other types of tumours is being actively explored by many researchers. One example is bombesin, a peptide known to have receptors in tumours of the breast, prostate and lungs. Bombesin has been labelled with ^{68}Ga and is being evaluated for its usefulness in imaging such tumours. In addition to the ^{68}Ge/^{68}Ga generator system, production is under way at various research centres of other potentially interesting generator systems for positron emitters, including, for example, titanium-44/scandium-44, selenium-72/arsenic-72 and neodymium-140/praseodymium-140.

H.1.2. Development of microfluidic-based synthesis systems for PET tracers

Methods for tagging biomolecules with fluorine-18 as immuno-PET tracers require extensive optimization of the radiolabelling conditions. Such processes tend to use up large amounts of scarce biomolecules. Microfluidic systems use small quantities of fluids containing active ingredients for the synthesis of PET radiopharmaceuticals. Microfluidic systems offer many advantages, such as more efficient chemical reactions due to very high surface to volume ratios, as well as fast and precise temperature control. Additional benefits are a highly controlled, flexible, reproducible and reliable production of radiopharmaceuticals thanks to process automation, and low-cost, interchangeable, disposable and quality-assured microfluidic key components. Meeting the radiation protection requirements for a microfluidic system is significantly less expensive due to its small size. Such a system also offers better space utilization in a laboratory. Microfluidic systems are particularly effective when scarce and expensive biomolecules are being considered for PET radiolabelling.

Recently developed digital microfluidic droplet generation (DMDG) chips can provide computer controlled metering and mixing of the fluorine-18 tag, the biomolecule and the buffer in defined ratios. This effectively allows rapid optimization of reaction conditions in nanolitre volumes, which can then be translated to bench-scale fluorine-18-labelling of cancer-specific engineered antibody fragments. These techniques, which became available in 2011, will have a significant impact on preclinical research and clinical applications of new PET tracers and, particularly, of immuno-PET tracers where the essential biomolecules are available in small quantities. New fluorine-18 labelling methods using microfluidics-based radiochemical synthesis technologies are being developed by a number of manufacturers worldwide.

H.1.3. Multi-particle cyclotrons for isotope production

One trend that could be observed in 2011 was that a number of manufacturers upgraded their cyclotron systems to increase the beam current and energies in order to meet the current demand for radionuclides used in clinical applications of single photon emission computed tomography (SPECT) PET, and therapy. The development of new versatile multi-particle isotope production cyclotrons capable of accelerating protons, deuterons, helium-3 and alpha particles in high intensities is a new trend in cyclotron technology, making it feasible to use beams other than proton for the production of reasonable quantities of radionuclides. Alpha beams can be used to produce new therapeutic isotopes such as the alpha emitter astatine-211 and the beta emitter copper-67. Although each radionuclide can be theoretically produced through several nuclear routes, the (p, n) reaction on an enriched target isotope is the most effective. The advent of multi-particle cyclotrons will widen the range of radionuclides as well as provide new routes for making available radionuclides of interest which have limited availability currently. For example, copper-64, iodine-124 and yttrium-86 which have proven use as well as the emerging radionuclides such as cobalt-55, bromine-76, zirconium-89, rubidium-82m, technetium-94m, iodine-120, etc. can be produced via the low energy (p, n), (p, α) or (d, n) reactions. The production of radionuclides such as iron-52, selenium-73, and strontium-83 using intermediate energy protons or deuterons requires special consideration in terms of subsequent chemical processing.

H.2. Radiation technology applications

H.2.1. Gamma-irradiated vaccine shows potential in the battle against malaria

Malaria is a potentially fatal parasitic disease affecting millions of people worldwide. Although vaccination procedures based on live attenuated virus-based vaccines have been successful for a number of infectious diseases — including polio, yellow fever, measles and small pox — developing an effective vaccine against *Plasmodium falciparum*, the most lethal of the malaria parasites, continues to be one of the great challenges of modern medicine.

At the most recent International Meeting on Radiation Processing (IMRP-2011), which was held in Montreal, Canada, in June 2011, researchers from Sanaria Inc., the National Institute of Standards and Technology (NIST) and Protein Potential reported the development of a highly effective vaccine based on radiation attenuated sporozoite that prevents malaria blood-stage infection, protecting the individual from disease and also blocking transmission of the disease. The reported vaccine is composed of metabolically active, non-replicating attenuated *Plasmodium falciparum* sporozoites (PfSPZ) produced by gamma irradiation. The challenge of manufacturing adequate quantities of vaccine that meet regulatory standards for initial clinical trials has been successfully met. Important objectives, such as establishing a radiation dose that attenuates all of the parasites without diminishing the potency, and developing a radiation methodology and monitoring system in full compliance with all the current good manufacturing practices mandated by the US Food and Drug Administration (FDA), have been accomplished successfully. A Phase 1 trial of the PfSPZ vaccine involving 80 volunteers has been completed and the efficacy of the vaccine demonstrated. The vaccine is now at an advanced stage of clinical trials and may replace existing vaccines that have a relatively high incidence of complications.

H.2.2. Radiation-grafted membranes help to clean contaminated water in the Fukushima area

The tsunami caused by the severe earthquake in Japan in March 2011 damaged the electricity supply and stopped the circulation of the cooling water of the nuclear reactor at the Fukushima Daiichi NPP. As a result of the meltdown of the nuclear reactor, radioactive materials were dispersed into the surrounding area, including into numerous water bodies.

In order to selectively remove radiocaesium from such contaminated water, a fibrous polymer absorbent, developed by the Quantum Beam Science Directorate (QuBS) of the Japan Atomic Energy Agency (JAEA) by radiation

FIG. H-1. Grafted membranes being used for removing radiocaesium from water in the Fukushima area (courtesy of JAEA Takasaki, Japan).

grafting of a suitable monomer onto polyethylene non-woven fabric was tested. The grafted absorbents folded in a cartridge were used to remove radiocaesium from a pond in Iitate-Mura, and from the swimming pool of a school in Fukushima city. Both of these tests were concluded successfully. An additional advantage of this technique is that not only is the radiocaesium removed, but that, as a result of the direct collection of the toxic component, no sludge is produced, thereby eliminating the need for additional handling and purification.

H.2.3. Electron beam technology for producing bioethanol from agroindustrial residue

According to the International Energy Agency (IEA)'s recently published *Technology Roadmap: Biofuels for Transport*, biofuels could represent 27% of all transportation fuels by 2050, compared to only 2% today.[50] This could significantly reduce CO_2 emissions while enhancing energy security, without harming food security if agroindustrial by-products are used. Conventional, or first generation, biofuels were produced from foodstuffs, such as corn and sugar cane, while the advanced, or second generation, biofuels are made from agroindustrial residues, such as straw, corn cobs and sugar cane bagasse. One example of biofuel is bioethanol, which has properties similar to petrol, but is sulphur-free and easily degradable, and offers farmers an alternative source of income other than the production of foodstuffs. Another benefit of a second generation biofuel such as bioethanol is the reduction of greenhouse gas emissions as compared to gasoline: studies have shown that sugar cane based ethanol reduces greenhouse gases by 86 to 90% if there is no significant change in land use.

The production of advanced biofuels is still at the development stage, since further improvements in conversion efficiency and cost reduction are required. In the case of bioethanol production from cellulose sources, one of the challenges is the slow and costly enzymatic hydrolysis of cellulose.

At the International Meeting on Radiation Processing in June 2011, it was reported that thermal hydrolysis (40 min, 180°C) combined with electron beam irradiation (50 kGy) of sugar cane bagasse led to a reduction in the amount of oligosaccharides formed by the partial decomposition of cellulose and hemicellulose. Earlier work by research groups in Brazil, Japan, the Republic of Korea and the USA indicated that electron beam irradiation of sugar cane bagasse with 30 kGy could enhance the enzymatic hydrolysis of cellulose by 75% and increase the yield of bioethanol.

[50] See *http://www.iea.org/papers/2011/biofuels_roadmap.pdf.*

FIG. H-2. Sugar cane harvesting in Brazil (courtesy of the Nuclear and Energy Research Institute (IPEN), São Paulo, Brazil).

H.3. Radiation technologies used in mining[51]

Radiotracers and nucleonic gauges are increasingly used in mining mainly for the exploration and effective exploitation of natural resources. While the more easily detectible radiotracers are used in non-invasive studies in the process industries, the nucleonic gauges are used for resource explorations. The deep penetration of neutrons and gamma rays makes nuclear techniques suitable for borehole logging applications which have hence been widely used in the oil, gas and uranium industries for a long time. Such techniques are now starting to be used in the coal and mineral mining industries also.

In addition, various nuclear spectrometry methods are successfully used in the fields and in industrial environments for in situ analysis of samples. The modern portable nuclear spectrometer offers enormous savings in time and labour without compromising the performance that matches the conventional laboratory instrument.

Mining, metallurgy and mineral processing industries are among the main beneficiaries of these techniques and technologies. Owing to the attractive benefits derived, use of radiotracers and nucleonic gauges in such industries is expanding and continuously evolving. New radiotracers, user friendly software, new detectors and data acquisition systems are being developed and introduced in practice.

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[51] Additional information is available in the appropriate attachment to the *Nuclear Technology Review 2012* on the General Conference web site.

Annex I

DEVELOPING ALTERNATIVES TO GAMMA IRRADIATION FOR THE STERILE INSECT TECHNIQUE

I–1. Introduction

Almost all insect pest control programmes currently releasing sterile insects as part of the area-wide integrated application of the sterile insect technique (SIT) use radioisotope irradiators that are loaded either with cobalt-60 or caesium-137, which produce ionizing radiation consisting of gamma rays. Irradiators such as the Gammacell 220 have proven to be extremely reliable for the purpose of achieving sterilization of target insect pests. However, the growing logistical complexities of the transboundary shipment of radioisotopes and the fear of terrorism are making the reloading of existing sources, the acquisition of new ones and their shipment to Member States across international borders increasingly difficult.

The situation was exacerbated in 2006, when the production of the Gammacell 220, the source most commonly used for irradiating insects for sterilization purposes was discontinued. Agency requests already issued to procure Gammacell 220 units for various technical cooperation projects were no longer honoured, thereby jeopardizing the implementation of many large on-going and new SIT programmes in Member States which depend on these units. The purpose of this annex is to provide an overview of efforts to develop alternatives to the use of gamma irradiation for SIT applications.

I–2. Search for Alternative Non-Gamma Radiation Sources

In response to these setbacks, the Agency initiated efforts in the mid-2000s to explore other options to sterilize insects for use in insect pest management programmes with an SIT component. Alternative technologies using low-energy X ray irradiation had at this time already been under development. Low-energy X ray irradiators emit X rays only when the electrical power is turned on, and consist of an X ray tube and a device to transport the insect canister through the X ray beam. The X ray tube consists of an electron source, generally a heated wire filament which acts as the cathode and emits electrons, and a high-atomic number target material as the anode from which X rays are generated. The electrons emitted by the cathode are not additionally accelerated, which means that no large and costly accelerators are needed, and because the energy is in the range of a few hundred keV, this requires much less shielding than in the case of gamma irradiators and allows the unit to be self-contained.

FIG. I–1. X ray irradiator (foreground) and water cooling unit (background).

In view of the high demand in Member States for sterilization hardware, technical advice and training, the Agency procured a low-energy X ray machine from a company that has a patent on the design of the X-ray tube used. Over the last years, the Agency has adapted, improved and validated the machine for insect sterilization.

I–3. Self-Contained Low-Energy X Ray Irradiators

For the past several years, self-contained low-energy X ray irradiators have been marketed for the specific purpose of blood irradiation (which requires a dose of about 25 Gy), and between 50 and 100 units are operating successfully at hospitals and medical institutes across North America. Following this success, a research irradiator with a radically different tube was developed, with a canister volume of about 1.5 litres and a dose rate of about 5 Gy/min, which is relatively low for insect irradiation (requiring a dose of about 100 Gy) on a commercial basis. Such irradiators have been upgraded in the last five years to yield dose rates of up to 100 Gy/min. This was achieved by changes in the design of the X ray tube, allowing a much higher power dissipation and improved dose uniformity.

These irradiators can be further configured (at additional cost) to address the requirements of the programme/customer in terms of dose and throughput. However, the X ray irradiator that was procured for the Insect Pest Control

Laboratory of the FAO/IAEA Agriculture and Biotechnology Laboratories in Seibersdorf, Austria, was an off-the-shelf product. It was delivered with a maximum energy of 150 keV and a variable current of 0–35 mA for a maximum total power requirement of just over 5 kW. It was supplied with its own external passive water cooling unit to remove the waste heat from the X ray tube.

This unit had one horizontal X ray tube and five horizontally aligned irradiation canisters made of cardboard that rotate around the irradiation tube. Such a configuration consumes 5.3 kW during operation and has a capacity to sterilize up to 20 litres of insects with 150 Gy in five minutes, or to decontaminate 10 litres of blood as diet for tsetse flies with 1 kGy in 30 minutes.

I–4. Development and Validation

The two main issues arising initially with the above X ray irradiator were related to reliability and dose rate and distribution. The X ray tube supplied with the machine failed repeatedly when the high voltage arced across the face of the insulator in the base of the tube. This caused the voltage from the high voltage power supply to collapse, without the possibility of recovery due to the conducting path formed by the arc. The only solution was to replace the sealing washer and silicone grease and remake the connection. This took approximately 30 minutes. However, each time an arc occurred, it caused further damage to the insulator, making it more likely that a new arc would form. After several such instances it became impossible to use the tube.

Consequently, the first X ray tube was replaced with a modified tube which had better cooling water flow around the tube, as well as an improved process for easier tube installation and exchange. This tube can now be operated at up to 45 mA rather than 35 mA. This increased the power output of the tube by about 28% with a corresponding increase in the dose rate. This tube has been in operation since 2009 without any problems, thereby confirming its greater reliability.

The second issue was related to dose distribution and dose rate. The machine was delivered with an original specification of a dose rate of 45 Gy/min, but the measured dose rate at the centre of a 180 mm diameter canister was only about 16 Gy/min. Further, and more importantly, the dose distribution within this volume was very poor, with the ratio of maximum to minimum dose (dose uniformity ratio (DUR)) being about 6. In a normal production environment, a DUR of 1.4 would be considered as acceptable.

The dose rate and DUR will vary with the diameter of the canister, the density of the material being irradiated and its distance from the tube. The density of the material cannot be changed, but the other two factors can. Dose rate and

FIG. I–2. Detail of X ray tube end cap insulator showing damage caused by high voltage arcing.

DUR will both improve (dose rate increase, DUR decrease) in a smaller diameter canister, whilst dose rate will decrease but the DUR will improve when the canister is further from the X ray tube. A 120 mm diameter canister was placed as far from the X ray tube as the machine permitted, giving a spacing of about 70 mm. In this configuration the central dose rate was about 20 Gy/min and the dose uniformity was greatly improved, with a DUR of about 1.6. The central region had a very good dose distribution (±5% in the central region of diameter 7 cm and length 10 cm) and the dose increased only slowly towards the outside of the canister (+15%), but the fall in dose towards the ends was much greater (–25–30%). To obtain the desirable DUR of 1.4 or better would require blocking off about 2 cm from each end of the canister to avoid the lowest dose areas, leaving a volume of just over 1.5 litres.

The smaller canister size (down from the original volume of four litres) is an important issue. It would increase the number of handling operations because it would require many smaller batches of insect pupae. As the dose only rises slowly around the centre line of the cylindrical canister, the working volume may be increased by increasing the diameter whilst reducing the length still further to obtain the desired DUR. Therefore a 160 mm diameter canister was tested, with thicker end walls to increase scatter. Based on the above it was estimated that a volume of three litres or more may be possible, and with the increased spacing

FIG. I–3. Improved canister design with internal 0.5 mm steel filter.

from the X ray tube it should be possible to accommodate six or eight canisters per irradiation.

I–5. Improving Dose Uniformity

It was realized that one of the causes of the poor dose uniformity was that X rays, unlike gamma radiation from a cobalt-60 source, contain a wide energy spread, from about 30 to 150 keV. In the case of an X ray irradiator, the low-energy X rays (photons) deliver a high dose at the surface near the entrance of the canister, resulting in a high DUR. Thus, the DUR could be decreased by ‘hardening’ the X ray energy spectrum by removing the low-energy photons before they reach the canister containing the pupae. A metal jacket around the canister can easily absorb these photons. The DUR for the bare canister (without metal surround) was 1.21 (considering only the direction along the diameter). Surrounding the canister with a jacket of brass 1 mm thick made this ratio almost unity. However, it also reduced the dose rate in the central region by about 70%.

On the other hand, surrounding the canister with a 0.5 mm steel jacket resulted in a DUR of about 1.06, and the dose rate reduction was only 40% as compared to that for the bare canister. Thus, for hardening the X ray spectrum in the irradiator, it is recommended to use canisters with a 0.5 mm steel jacket.

The axial and radial dose distributions for the final geometry of the canister were also determined. These measurements were made with all five canisters full of instant rice (which behaves very similarly to insect pupae under irradiation). Two separate runs were made; one for axial dose distribution and the other for radial dose distribution. For the axial run, three 20 cm-long Gafchromic® films were placed within the canister along its length: one in the centre (along the axis) and two near the periphery (laid on the curved surface). For the radial run, two 18 cm-long Gafchromic® films were placed perpendicular to each other and both along the diameter going through the centre of the canister. For both runs, the irradiator was operated at 150 kV and 17.5 mA for 20 min, with a rotation speed of 5 rpm. Low current was selected so that there would be several revolutions of the canisters, meaning that the dose distribution is not significantly affected by the last, incomplete revolution. For these measurements, the canister was 20 cm long. To achieve a DUR of 1.3, the canister was shortened to 15 cm, yielding a volume of just over 3.7 litres. Thus 18 litres of pupae can be irradiated per batch.

The dose rate in the centre of the canister filled with instant rice was about 14 Gy/min. When the canister was filled with fruit fly pupae the dose rate decreased by 6%. This dose rate was measured by a Farmer type (0.18 cm^3) ionization chamber which was calibrated in the energy range of 40 keV to 1.33 MeV with traceability to the National Institute of Standards and Technology (NIST) in the USA. Such a reference dosimetry system is essential for the calibration of the routine Gafchromic® dosimetry system.

The machine also had to be significantly modified in terms of an improved carousel system and new canisters, as well as some other changes. The new carousel system allowed more precise alignment of the canisters with the X ray tube and has made the canisters much more secure so that they should now not be able to become dislodged. The canisters themselves are now made of carbon fibre reinforced resin, which is lightweight, waterproof and almost transparent to X rays, and have the steel filtration incorporated inside. The length and longitudinal positioning of the canisters has been adjusted to give a good DUR of less than 1.3. Various inserts have been developed such as for the irradiation of mosquito pupae.

In addition, the software used to operate the X ray machine had to be revised to permit the selection of a predetermined energy rather than a fixed power and time, and to protect specific sections of the program with a password to prevent unintended modification.

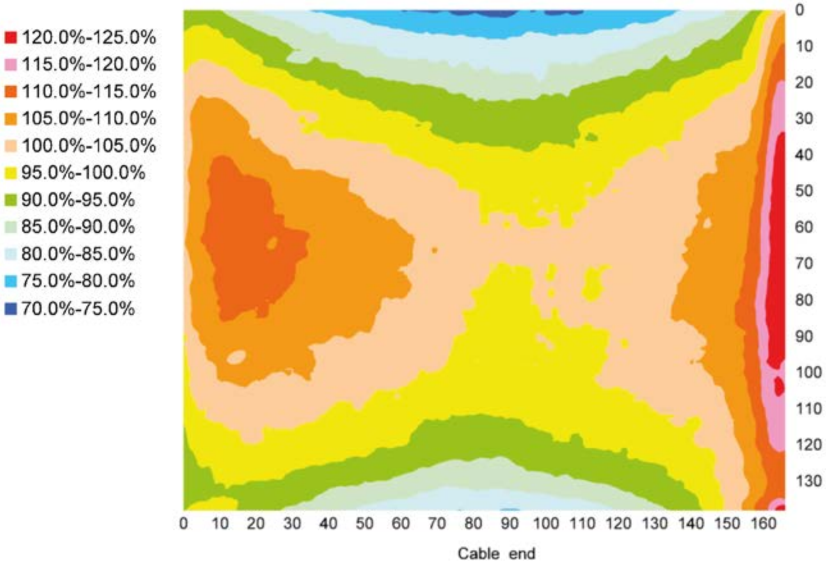

FIG. I–4. Dose distribution map in a canister with 0.5 mm steel filter.

I–6. Development of Dosimetry

During this development work it became apparent that there were also problems with the Gafchromic® routine dosimetry system. The standard procedure used during cobalt-60 irradiation does not work for X ray irradiation, as the Gafchromic® film is much more sensitive at these low energies to the material surrounding it, in the range of a few hundred micrometres. Extensive tests have clarified the necessary conditions for using Gafchromic® film dosimeters with the X ray machine, the principal one being that the film must always be enclosed in the same material. The recommendation is to use standard dosimeter envelopes made out of paper. A separate calibration from that used with gamma irradiation is also required.

During this improvement/validation process it turned out that the existing Standard Operating Procedure for Gafchromic® Dosimetry needs revision for low energy X-radiation. Consequently a new SOP was prepared and a new version of the original SOP specifically for gamma radiation using cobalt-60 or caesium-137 has also been prepared. In order to further enhance the dosimetry and to simplify the calibration of X ray sources, the Agency, in collaboration with Centro Estrategico de Pesquisa, Tecnologia e Inovacao — CETECBR in Pernambuco, Brazil, will continue to work on developing and characterizing an

FIG. I–5. Canister insert for irradiation of mosquito pupae showing the nested trays used to hold the pupae in a minimum quantity of water.

alanine/electron spin resonance (ESR) dosimetry system to use as a transfer standard dosimeter, and to establish a dosimetry service in Member States.

I–7. Biological Efficacy

Trials have been carried out to determine the differing effects, if any, between sterilization of insects with ionizing energy sourced from cobalt-60 (gamma irradiation) or from an X ray source. As the FAO/IAEA Agriculture and Biotechnology Laboratories in Seibersdorf have both types of irradiators on-site it is in a unique position to test for any differences in the effectiveness of the two systems with regard to their use in SIT programmes. Three fruit fly pest species were assessed: the South American fruit fly *Anastrepha fraterculus,* the melon fly *Bactrocera cucurbitae*, and the Mediterranean fruit fly *Ceratitis capitata*. Pupae of the same age were irradiated at the same nominal doses in either the X ray machine or a gamma irradiator and their quality assessed under the same conditions. Dosimetric procedures conducted after treatment determined actual doses received by the pupae. Figure I–6 shows the effects of radiation which can be seen when dissecting the male and female reproductive organs of irradiated

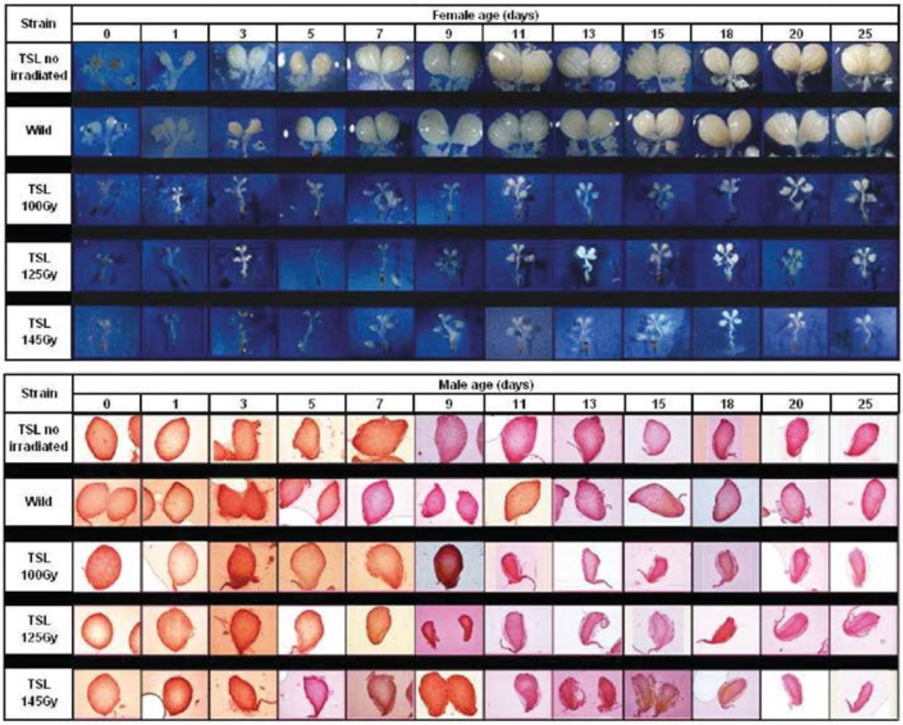

FIG. I–6. Effect of gamma irradiation (100, 125 and 145 Gy) and no irradiation on female (upper) and male (lower) reproductive systems of the Mediterranean fruit fly (comparing wild flies and temperature sensitive lethal (tsl) genetic sexing strain developed by the Agency).

fruit flies, in particular the deterioration of ovaries in females and of spermatogenesis in males. Tests on the treated and untreated insects included standard quality control procedures for sterile and fertile males and females. Eggs from pairings of irradiated males with non-irradiated female flies gave a measure of the residual fertility of the insects treated with either gamma rays or X rays (see Table I–1). For each sterility level calculated (50%, 90% and 99%), the relative biological effectiveness (RBE) of gamma radiation did not differ significantly from that of X rays, and adult emergence rates and mating competitiveness between gamma ray and X ray treated males competing for fertile females in field cages have so far revealed no significant differences.

I–8. Conclusion

Agency efforts to develop alternatives to the use of gamma irradiation in SIT applications have succeeded, as shown by the similar radiation effects

TABLE I–1. COMPARISON OF GAMMA AND X-RADIATION DOSES (Gy) CALCULATED FROM THE LINEAR REGRESSION EQUATIONS OF PROBIT STERILITY ON LOG DOSE FOR SELECTED STERILITY LEVELS AND THEIR ESTIMATED RBE VALUES

Pest species	Treatment	D_{50}[a]	RBE[b]	D_{90}	RBE	D_{99}	RBE[b]
C. capitata	X rays	20.4 (17.9; 23.2)[c]	1 (0.8; 1.1)	46.8 (41.5; 54.1)	1 (0.9; 1.1)	91.2 (83.6; 101.3)	1 (0.9; 1.1)
	γ-rays	27.9 (22.9; 33.9)	0.7[ns, d] (0.5; 1.0)	63.8 (53.9; 75.8)	0.7[ns] (0.4; 1.0)	124.9 (94.9; 160.9)	0.7[ns] (0.5; 1.0)
A. fraterculus males	X rays	13.0 (9.02; 18.8)	1 (0.8; 1.3)	23.5 (18.8; 29.8)	1 (0.9; 1.2)	37.8 (27.7; 52.1)	1 (0.8; 1.2)
	γ-rays	7.6 (5.3; 11.1)	1.7[ns] (0.4; 6.9)	18.2 (15.3; 21.9)	1.2[ns] (0.3; 5.1)	36.3 (27.8; 49.4)	1.04[ns] (0.3; 4.1)
A. fraterculus females	X rays	27.1 (17.7; 41.4)	1 (0.7; 1.4)	41.2 (25.4; 68.3)	1 (0.7; 1.4)	57.8 (30.1; 109.7)	1 (0.6; 1.6)
	γ-rays	23.8 (15.1; 36.7)	1.1[ns] (0.3; 4.4)	38.6 (21.3; 71.2)	1.1[ns] (0.3; 4.2)	57.3 (25.7; 125.4)	1.01[ns] (0.2; 4.4)

[a] D = dose (Gy) that induces 50%, 90% or 99% sterility.
[b] RBE = relative biological effectiveness (relative to X rays).
[c] Confidence interval stated at 95% confidence level.
[d] When the confidence interval includes the value 1 for D50, D90, or D99 RBE, then the D50, D90, or D99 values are not significantly different ($P > 0.05$; ns, not significant).

obtained for insects irradiated with gamma rays and with X rays. It is hoped that these results will stimulate the development of more X ray based irradiation systems in order to increase competition and bring down the prices of equipment used in Member States. After completing the characterization of the X ray irradiator, the Agency ordered several units for use in Member States. These new machines incorporate all the changes and modifications that were identified during the testing phase at the FAO/IAEA Insect Pest Control Laboratory in Seibersdorf, Austria. One unit has now been operating without any problems for several months in a fruit fly SIT programme in Brazil, another was installed in Costa Rica in late 2011, and additional units will shortly be installed in Burkina Faso and Pakistan. Nevertheless, it will take several years to collect sufficient data to assess whether this really is a viable alternative to the sterilization of insects at mass rearing factories under routine large-scale operational conditions.

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Annex II

IMAGING FOR BREAST CANCER HELPS IN DIAGNOSIS AND TREATMENT

II–1. Background

The purpose of this report is to provide an overview of the role of imaging for diagnosis, treatment planning and follow-up of breast cancer. Breast cancer is the most common non-skin type malignancy and the second leading cause of cancer mortality in women, as well as the most common female cancer in both developing and developed countries [II–1]. It arises from the breast tissue, most commonly from the inner lining of milk ducts (ductal carcinoma) or, less frequently, from the lobules that supply milk to the ducts (lobular carcinoma) [II–2].

Although breast cancer incidence, mortality and survival rates vary by as much as four-fold in different geographical regions of the world, its incidence is increasing in the world as a whole. Nevertheless, the age-standardized rate (ASR) still remains almost three-fold higher in developed than in developing areas (more than 80 versus less than 30 new cases per 100 000 per year, respectively) [II–3]. On the other hand, mortality is growing especially in those regions of the world without early detection programmes [II–4], so that the pattern of mortality across different countries does not consistently mirror incidence (see Fig. II–1).

Interestingly, higher socioeconomic conditions have been reported to be associated with an increased risk of breast cancer mortality. In fact, longitudinal data on breast cancer mortality according to educational level and marital status obtained from different European countries (Austria, Belgium, Denmark,

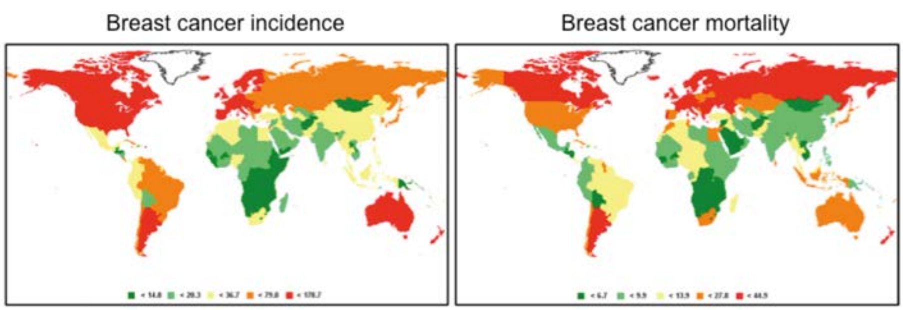

FIG. II–1. Patterns of distribution of breast cancer incidence and mortality worldwide (modified from WHO/IARC data retrieved from <http://globocan.iarc.fr/>, last access on 18 November 2011).

England, Wales, Finland, France, Norway, Switzerland) or from individual cities (Barcelona, Madrid, Turin) showed a positive association in all populations, except for Finland and France (and for Barcelona among the cities). As a persistent and generalized observation across Europe in the 1990s, women with a higher educational level had an approximately 15% greater risk of dying from breast cancer than those with lower education, a common feature for both married and unmarried women [II–5].

II–2. Risk Factors

Age, family history and genetics, late first pregnancy and obesity are well-established risk factors for breast cancer [II–6]. Most women with breast cancer are postmenopausal although breast cancer is not uncommon in premenopausal women and is often more aggressive in this group. The recognition of gene mutations in the germ cell line [II–7] (for example, in the BRCA1 gene) is a major advance in understanding the basis of inherited disease; in this regard, the genetic profilI–e is now being increasingly incorporated in breast cancer risk assessments, particularly for families prone to breast cancer at an early age.

II-3. Staging and Prognosis

The most crucial parameters for newly diagnosed breast cancer are staging at the time of diagnosis and receptor status.

Stage: According to the American Joint Committee on Cancer, the TNM parameters for staging breast cancer include size of the tumour (parameter T), whether or not the tumour has spread to the axillary lymph nodes (parameter N), and whether or not the tumour has metastasized (parameter M) (i.e. spread to a more distant part of the body). Larger tumour size, nodal spread, and distant metastasis have worse prognosis, as also have increasing levels of overall stage, from early-stage disease (stage I) to late-stage metastatic disease (stage IV). In this regard, improved diagnosis and staging, especially sentinel lymph node mapping, has resulted in recent updates in the staging definitions [II–8].

Prognosis: Breast cancer cells have receptors on their surface and in their cytoplasm and nucleus. Binding of specific ligands (such as hormones) to these receptors causes changes in cell biology. The most important receptors for breast cancer cells are: estrogen receptors (ERs), progesterone receptors (PRs), and epidermal growth factor receptors (HER2/neu). The growth of breast cancer cells expressing ERs is stimulated by estrogens, so that certain drugs blocking the estrogen effects (e.g. tamoxifen) can effectively be employed to treat cancers that usually have a better prognosis than the ER-negative cancers. On the other hand, while HER2-expressing breast cancers have a worse prognosis than the HER2-negative cancers [II–9], the HER2+ cancer cells respond well to the monoclonal antibody trastuzumab (in combination with conventional chemotherapy); such pattern has significantly improved the prognosis of these cancers [II–10]. Breast cancer cells expressing none of these receptors are called basal-like or 'triple negative'.

II–4. Screening and Diagnosis of Breast Cancer

Imaging plays a crucial role for breast cancer screening, for classifying and sampling non-palpable breast abnormalities, as well as for defining the extent of breast tumours, both locally, loco-regionally, and at distant sites. Evaluating response to therapy constitutes an additional important role of imaging. Therefore, imaging via different modalities represents an essential, life-long component for patients with breast cancer, from initial diagnosis throughout the evolution of the disease.

Most breast cancers are detected by physical examination or via a mammography as part of a screening programme [II–11].

II–4.1. X ray mammography

Mammography uses low-energy X rays (usually around 30 kVp) to examine the breast and is the primary imaging modality for breast cancer screening, detection and diagnosis. The goal of a screening mammography programme is to detect small (<1 cm) tumours, typically through identification of characteristic masses and/or microcalcification (see Fig. II–2).

Mammographic screening is generally suggested to the asymptomatic 40–45-year-old female population at 2-year intervals, while the American Cancer Society and the American College of Radiology recommend yearly mammograms beginning at the age of 40 years. In case of a normal screening mammogram, the woman is simply invited to the next round of screening. Successful mammographic screening leads to cancer detection at average earlier stage and with smaller size of the lesions which in turn reduced breast cancer mortality [II–12].

While excisional biopsy has been for some time commonly employed to ascertain the histological nature of suspicious lesions detected during mammography, this practice has now been largely replaced by stereotactic core needle biopsy. Mammography is also used to guide placement of hook-wire needles for intraoperatively localizing non-palpable tumours (e.g. a breast cancer detected by microcalcifications); nevertheless, this procedure is now being

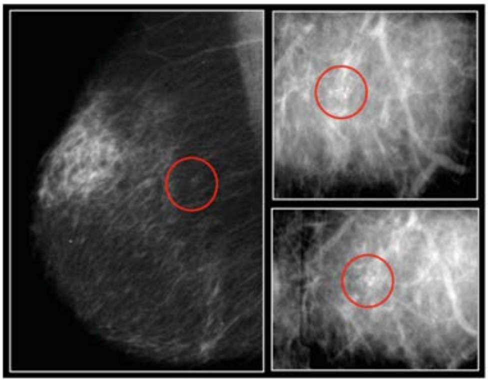

FIG. II–2. Example of early, in-situ breast cancer detected by screening mammography in a 52-year old woman. Suspicion of cancer is raised by detecting an area with microcalcifications (indicated by red circles) in the breast; images in the right panels represent enlarged details of the same area in two different projections.

increasingly replaced by a procedure called ‘radio-guided occult lesion localization’ (or ROLL) based on the intralesional injection of radiolabelled particles (^{99m}Tc-macroaggregates of human albumin, or ^{99m}Tc-MAA) that do not migrate from the site of interstitial administration and on subsequent use of a hand-held gamma probe for intraoperative guidance. Moreover, mammography is used to define the extent of malignancy before definitive breast-conserving surgery as well as to monitor the breast after surgery and external beam radiation therapy.

Both ultrasound examination and magnetic resonance imaging (MRI) are important complementary modalities to X ray mammography for diagnosing, characterizing and determining the extent of breast cancer (see Fig. II–3); while ultrasound is routinely utilized in these roles [II–13], the routine use of MRI is still limited by local logistical and availability constraints.

II–4.2. Ultrasound

Ultrasound (US) is routinely used in breast imaging centres as an essential complement to physical examination and mammography for the evaluation of breast masses. US not only differentiates cystic from solid masses, but also aids in discriminating benign from malignant solid masses (see Fig. II–3). Moreover, in patients with newly diagnosed breast cancer, US of the regional lymph node basins (with US-guided fine-needle aspiration of suspicious nodes) can alter the pre-therapeutic stage. US can also be used to evaluate the treated breast and to detect and diagnose local recurrences. However, US cannot demonstrate

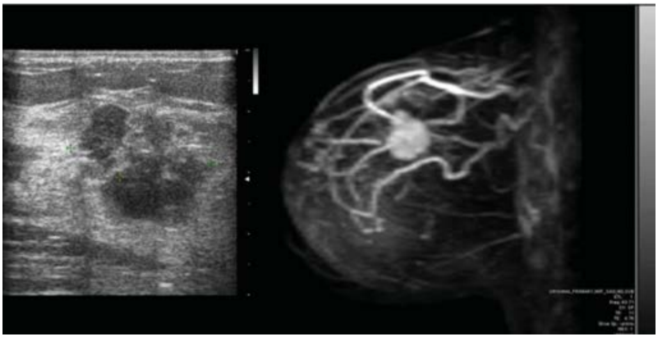

FIG. II–3. Imaging results obtained in a 40-year old woman included in the regular screening programme for mammography show a mass with irregular margins in the upper inner quadrant of the left breast (maximum diameter 25 mm; image not available because performed in another centre). The patient was then referred for further characterization. Left panel: US imaging confirms the inhomogeneous mass with irregular margins in the left breast. Right panel: MRI with gadolinium contrast shows that the mass has ductal-type contrast enhancement, suggesting breast cancer (confirmed by needle core biopsy as infiltrating ductal carcinoma).

microcalcifications, and its accuracy is highly operator-dependent. Although US can detect some non-palpable carcinomas missed by mammography, its efficacy for breast cancer screening per se remains to be proved. Because of its unique real-time capability, US has become the modality of choice for guiding percutaneous interventional procedures on breast masses, from needle biopsy to ablation.

II–4.3. Magnetic resonance imaging

Magnetic resonance imaging (MRI) shows great promise for detecting mammographically occult breast cancers and for defining the extent of malignant disease (see Fig. II–3). MRI-guided needle localization and core needle biopsy techniques have been developed to complement the increased utilization of MRI for breast cancer staging [II–14]. MRI has also shown to be of value for screening in women at high risk of breast cancer, and has therefore recently been incorporated in the American Cancer Society recommendations for screening [II–15].

II–4.4. Positron emission mammography

Cancer imaging by positron emission tomography (PET) with [^{18}F]fluoro-2-deoxy-D-glucose ([^{18}F]FDG) is based on enhanced uptake of

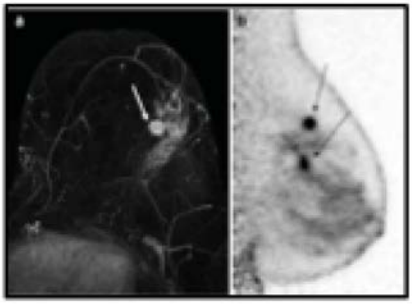

FIG. II–4. 61-year-old woman with an area of clustered pleomorphic microcalcifications in the upper outer quadrant of the left breast which proved to be ductal carcinoma in-situ following stereotactic biopsy. US identified an additional 7-mm nodule in the same quadrant. Core sampling found this nodule to be invasive ductal carcinoma. MRI identified a 1.2-cm irregular enhancing mass (depicted by arrow) with a possible satellite lesion (left-hand image). PEM confirmed a 1.1 × 1.0 × 2.2-cm mass with a second 0.7 × 0.7 × 2.5-cm inferior mass with final pathology confirming the two cancer lesions (right-hand image), as depicted by arrows [reproduced from Schilling, K., et al., Positron emission mammography in breast cancer presurgical planning: comparisons with magnetic resonance imaging. Eur J Nucl Med Mol Imaging. 38 (2011) 23–36. The original publication is available at www.springerlink.com.]

[^{18}F]FDG by tissues with increased metabolic demand versus their normal tissue. The large-scale diffusion of [^{18}F]FDG PET imaging (and especially PET/CT) for whole-body analysis in the evaluation of the majority of tumours has raised interest in its use to diagnose primary breast cancer. The primary diagnosis of breast cancer is best achieved with the use of dedicated devices for positron emission mammography (PEM). In this regard, although whole-body [^{18}F]FDG PET has a certain diagnostic accuracy for detecting malignant breast lesions, its sensitivity is lower than that of other standard diagnostic imaging techniques (see Fig. II–4).

The dedicated PEM devices have several advantages compared to whole-body PET, such as higher geometric sensitivity and spatial resolution, shorter imaging time, reduced attenuation, compression capability and small physical footprint (that allows correlation with X ray mammography and permits PEM-guided biopsy) [II–16, II–17]. Although early studies confirm the high diagnostic accuracy of PEM, clinical data are still limited, particularly compared to the large amount of data supporting the existing breast-imaging methods

II–5. Imaging for breast cancer staging

In patients with a known or highly suspected cancer, staging is performed to determine the extent of spread and overall burden of the disease. It includes evaluation of the affected breast, of regional lymph nodes, and of distant or systemic sites. Results of staging are stratified according to the TNM system [II–18].

Assessment of the T parameter in patients with breast cancer is commonly based on X ray mammography, US and MRI, as described above for diagnostic characterization of suspicious tumour lesions.

Lymph node status (parameter N) is a major prognostic factor in early-stage disease and this information is of paramount importance for tailoring patient-specific treatment. In particular, the presence or absence of metastatic infiltration of the axillary lymph nodes must be considered for further treatment after surgery (adjuvant therapy). In the preoperative phase, the axillary status can be assessed by clinical examination (low sensivity/specificity), US (sensitive and inexpensive, possibly integrated with fine-needle aspiration cytology to increase specificity), and by PET/CT with [^{18}F]FDG (over 95% specificity, but low sensitivity for nodes <1 cm in size, and high cost). Therefore, most patients are scheduled for surgery without the axillary lymph node status having been ascertained accurately.

The traditional approach to axillary nodal staging has for several decades been represented by systematic axillary lymph node dissection. However, this procedure is frequently burdened with important immediate and long-term morbidities (such as wound infection and prolonged healing, sensory/motor nerve damage and, above all, lymphoedema of the upper limb). These drawbacks are especially important when considering that complete axillary dissection is actually necessary in only about one out of three patients with early breast cancer. In the past few years, the procedure of sentinel lymph node biopsy for predicting tumour status of the axilla has become the standard of care for breast cancer patients with a clinically negative axilla. This procedure is best performed as radio-guided biopsy of the sentinel lymph node, after lymphoscintigraphic mapping with the use of a radiocolloid agent that is injected interstitially at the tumour.

Staging for distant metastases (parameter M) as part of the initial evaluation is recommended for locally advanced breast cancer, especially for patients with advanced axillary nodal disease, because in these conditions the risk of systemic metastases is high. In these cases imaging is designed to survey the chest, abdomen, pelvis and bones; it generally includes standard chest X ray or computed tomography (CT), abdominal ultrasound or CT, and bone scintigraphy (see Fig. II–5).

In early-stage breast cancer patients (Stage I or low-end of Stage II), systemic staging is not recommended, unless symptoms are present, since the

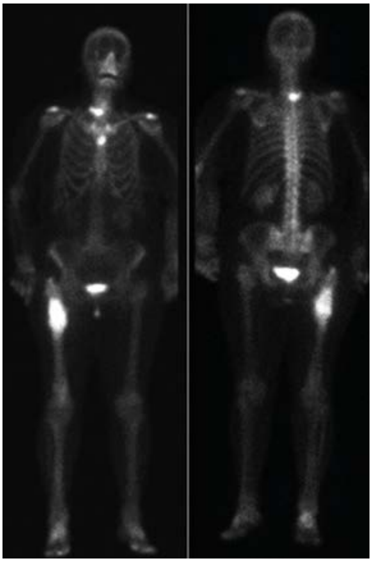

FIG. II–5. Bone scintigraphy obtained after intravenous injection of ^{99m}Tc-MDP in a 61-year old patient with newly diagnosed breast cancer in whom the scan was performed for preoperative staging. There are multiple areas of markedly increased uptake corresponding to previously unknown, asymptomatic metastatic lesions in the cervical spine, in the sternum, and in the upper third of the right femur. Such metastatic diffusion disqualifies the patient from curative surgery of the primary tumour.

chance of distant metastases is low and therefore the chance of false positive findings is considerably higher than the chance of true positive findings.

II–5.1. Radio-guided sentinel lymph node biopsy for staging

The high morbidity of axillary lymph node dissection (see above) has stimulated the development of a less traumatic but equally accurate approach, i.e. sentinel lymph node biopsy. The term 'sentinel lymph node' indicates the first lymph node encountered by lymphatic vessels draining the primary tumour, or the first lymph node upon which a lymph vessel originating in the tumour drains directly. This definition does not always correspond to the lymph node nearest the tumour, as the route of the lymphatic vessels is often tortuous and unpredictable. There may be different lymphatic pathways draining certain tumour sites, leading to different sentinel lymph nodes (see Fig. II–6); each sentinel node should therefore be investigated for the presence of metastasis.

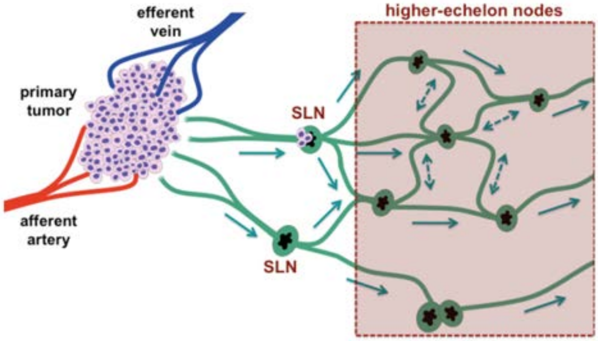

FIG. II–6. Assuming that lymph drainage from a solid tumour proceeds in an orderly way from lower-echelon to higher-echelon nodes, the first node(s) encountered in such pathway, i.e. the sentinel node(s), is the site where tumour cells contained in the lymph are most likely to originate metastasis before involving higher-echelon lymph nodes. In any given lymphatic basin there can be more than one sentinel lymph node, as lymph drainage can occur via different channels towards the same basin. Complex interconnections occur also at higher levels, with variable directions of lymph flow at intermediate levels within the general pattern of centripetal flow.

Typically, for sentinel lymph node mapping, a colloidal radiopharmaceutical (^{99m}Tc-sulphur colloid or ^{99m}Tc-albumin nanocolloid) is injected, and sentinel nodes are identified in the preoeperative phase through lymphoscintigraphy, and in the operative phase with a gamma probe.

Interstitial administration of a small amount of radiopharmaceutical is usually performed through US-guided peritumoral injection or through intra/subdermal injection over the tumour, and/or through periareolar injection. Since lymph drains from the intra/subdermal space to the subcutaneous plexus (where lymph originating from the underlying breast parenchyma also merges), a radiocolloid injected intra/subdermally displays the same pathways of lymphatic drainage as the underlying breast gland and of cancer cells entering the lymphatic space.

Lymphoscintigraphy is an integral step for radio-guided sentinel lymph node biopsy, because it is particularly useful to identify not only axillary sentinel lymph node(s) as a guide to subsequent removal aided by intraoperative gamma probe counting, but also draining lymph nodes in other unusual lymphatic basins, especially the internal mammary chain or even infraclavicular lymph nodes. Such lymph node mapping is best performed by single photon emission computed tomography (SPECT), and especially by SPECT/CT rather than by simple planar imaging (see Fig. II–7). At the end of lymphoscintigraphy, cutaneous projection of the sentinel lymph node is marked with a dermographic pen.

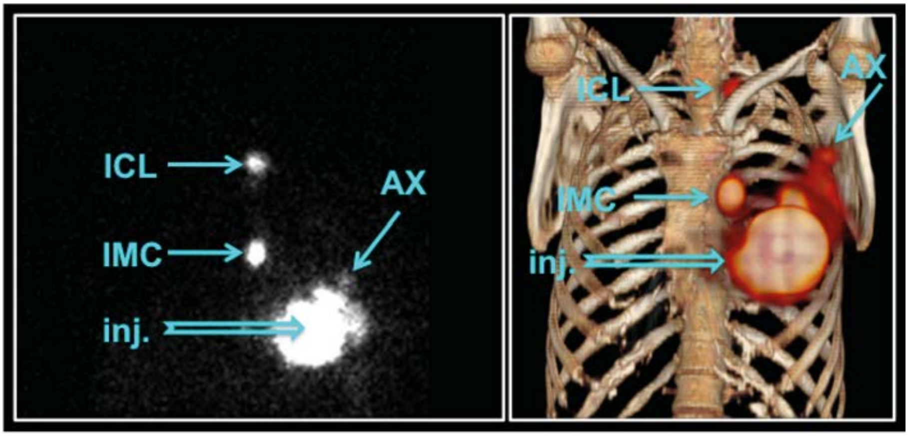

FIG. II–7. Lymphoscintigraphic mapping obtained after peritumoral injection of 99mTc-nanocolloid in a patient with cancer of the left breast scheduled for surgery and radioguided sentinel lymph node biopsy. Planar images (left panel) show migration of the radiocolloid from the injection site to an axillary sentinel lymph node as well as to additional sentinel nodes in the internal mammary chain and in the infraclavicular space. Topographic location of such lymph nodes, that guide the surgeon for removal, are better shown by 3D volume rendering of a SPECT/CT acquisition (right panel). inj. = injection site; AX = axillary sentinel node; IMC = internal mammary chain sentinel node; ICL = infraclavicular sentinel node.

In the operating theatre, the surgeon utilizes a hand-held, highly collimated probe for gamma counting (the ‘gamma probe’) to localize lymph nodes that have retained the radiocolloid, usually with very high target/background ratios (at least 10:1). These devices do not produce any scintigraphic images, but they yield both a numerical readout and an audible signal proportional to the counting rate; the latter signal, in particular, guides the surgeon to the radioactive target without distracting his/her visual attention from the surgical bed. The sentinel lymph node and any other radioactive nodes so identified are sent for intraoperative frozen-section analysis (and subsequently processed for definitive staining and histology). Analysis of sentinel lymph nodes is extremely effective and can detect the presence of macrometastasis. [II–19].

In case of sentinel node(s) free from metastasis, the patient can be spared the full axillary dissection because the likelihood that non-sentinel lymph nodes contain metastasis is extremely low, thus making extensive dissection unnecessary. Patients whose sentinel lymph node contains metastasis usually require dissection of regional lymph nodes to determine the extent of axillary metastatic spread [II–20].

II–5.2. Radio-guided occult lesion localization (ROLL)

With the widespread availability of breast cancer screening programmes, breast cancer is being increasingly detected at an earlier stage, and some of the lesions may not be palpable. Several techniques have been developed to assist the surgeon in exactly locating these small cancer foci to facilitate excision during surgery, such as percutaneous introduction of a marker (a needle or wire) during a stereotactic or US-guided biopsy. Recently, a radioguided technique based on direct intralesional injection of a radiopharmaceutical constituted by relatively large particles that do not appreciably move from the site of interstitial injection (such as ^{9m}Tc-macroaggregates of albumin, with a size range of 10–150 µm) has been developed and largely validated. In the operating theatre, the exact location of the tumour is identified with the help of a gamma probe, which is introduced through the surgical incision and thus helps to easily localize the focal deposition of the radiopharmaceutical (and the tumour). This technique is now being increasingly performed for non-palpable breast lesions, and in several centres around the world it is now considered the routine standard procedure for such clinical condition [II–21, II–22, II–23].

II–6. [^{18}F]FDG PET/CT in patients with breast cancer

II–6.1. Overall staging

The introduction and diffusion of advanced cancer imaging with hybrid PET/CT equipment is having an increasing impact on the clinical management of patients with breast cancer (as well as in patients with a variety of other malignancies). In fact, this technique yields crucial information on the locoregional and whole-body burden of metabolically active disease [II–24], and therefore leads to treatment strategies tailored to the individual patient's conditions, from the phase of initial staging after diagnosis (see above) to the phase of assessing response to anti-tumour therapy [II–25].

Besides its use for initial staging of the axilla (see above), [^{18}F]FGD PET/CT is now being recommended for systemic staging in patients with locally advanced breast cancer, i.e. either a primary tumour larger than 5 cm, and/or skin or chest wall tumoral involvement, fixed axillary nodes, positive supraclavicular/infraclavicular and/or internal mammary chain lymph nodes, and inflammatory cancer (see Fig. II–8). Currently, the standard curative approach with these patients consists of neoadjuvant chemotherapy followed by surgery with axillary nodal dissection and external beam radiation therapy.

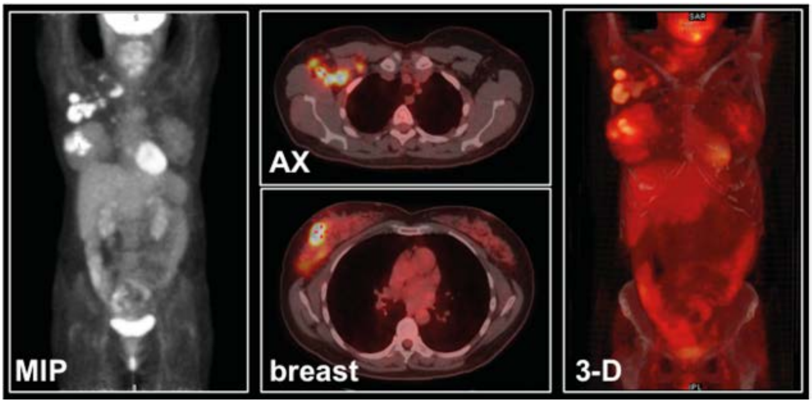

FIG. II–8. Example of [^{18}F]FDG PET/CT in a 58-year old patient with locally advanced cancer of the right breast. The maximum-intensity-projection image in the left panel (MIP) and the 3-D volume rendering in the right panel (3-D) show overall tumour involvement as areas with markedly increased [^{18}F]FDG uptake in the breast and in lymph nodes of the axilla, but also extending to infraclavicular nodes (and possibly to internal mammary chain nodes). Selected fused transaxial PET/CT sections at different levels (breast in lower, axilla in upper middle panels) demonstrate in greater detail the anatomo-topographic correlations of the primary tumour and of its lymph node metastases.

However, some of these patients may have occult distant metastases, and therefore aggressive therapies with curative intent may not be indicated. The presence of distant metastases is also an important prognostic factor in patients with newly diagnosed early breast cancer, and the extent of metastatic disease affects the therapeutic options. [^{18}F]FDG PET/CT is reported to be highly sensitive and specific for detecting additional sites of loco-regional lymph nodal spread and/or distant metastases not detected by standard imaging, thus changing staging in up to 25% of the cases. On the other hand, MRI is the method of choice for detecting brain metastasis. Therefore, [^{18}F]FDG PET/CT should complement conventional staging procedures and should not be considered as a total replacement for either bone scintigraphy or diagnostic CT [II–26].

II–6.2. Assessment of the efficacy of anti-tumour therapy

[^{18}F]FDG PET/CT has been shown to be particularly useful for restaging breast cancer both in patients with rising tumour markers and negative/equivocal findings at conventional imaging, and for evaluating response to therapy [II–27]. In fact, there is increasing clinical evidence for breast cancer and other tumours that post-treatment [^{18}F]FDG PET/CT is the most accurate procedure for assessing response to therapy, both in the neoadjuvant setting and in case of tumour recurrence after primary treatment. The concept of using [^{18}F]FDG PET/CT for predicting a therapeutic response is based on an early decrease in glucose metabolism (instead of changes in size, that generally occur later when evaluated by other conventional imaging modalities); such reduction in glucose consumption is closely correlated with the efficacy of therapy. In particular, [^{18}F]FDG PET/CT has been shown capable of discriminating patients as responders from non-responders earlier than CT and/or MRI [II–28].

During the course of their disease, about 30% to 85% of patients with recurring and/or metastatic breast cancer develop bone metastases, mostly to the spine and pelvis, followed by ribs, skull and femur. Although bone scanning with ^{99m}Tc-labelled phosphonates is the most commonly used method for staging bone metastases, the high sensitivity of this technique is counter-balanced by low specificity, since false positive findings can be due to trauma, degenerative changes, and other benign conditions; on the other hand, false negatives can occur in the presence of metastases with predominantly osteolytic patterns and low bone turnover. The availability of a bone-seeking PET agent such as ^{18}F-fluoride (that accumulates by chemio-adsorption at sites of increased bone turnover) has increased the potential clinical applications of PET/CT imaging also for evaluating bone involvement, e.g. by metastasis. This imaging technique is much more sensitive (and also more specific) than conventional bone scintigraphy with ^{99m}Tc-labelled bone-seeking agents. Nevertheless, several cost and availability issues must be adequately addressed before this imaging technique can be recommended for patients with breast cancer, especially considering that bone metastases from this tumour tend to be osteolytic or intramedullary and are therefore likely to be better detected by [^{18}F]FDG PET/CT than are osteoblastic lesions [II–29, II–30].

II–7. Challenges and possible responses

All the diagnostic and therapeutic strategies outlined above presuppose nationwide availability of both state-of-the-art diagnostic imaging equipment and implementation of adequate screening programmes and of procedural guidelines for treatment of breast cancer patients, be it single modality or multiple modality therapies. However, this is most often not the case. In particular, while in developed countries with high standards of care the current economic constraints raise issues concerning optimization of procedures and resources, in developing countries more basic issues frequently arise, such as the availability of adequate equipment, logistics, the availability of trained human resources, the existence of a national health care service, and access to health facilities. For instance, the reduced availability of PET/CT (labour-intensive equipment that is relatively expensive in terms of acquisition, setup, daily operation, and well-trained technical and medical personnel) limits the impact of this procedure which is potentially cost-saving if employed systematically according to well-established clinical guidelines.

A paradigm of this situation is represented by radio-guided sentinel lymph node biopsies, the clinical impact of which is most beneficial for those patients with early rather than advanced breast cancer. Various determinants (from socioeconomic and geographic in terms of accessibility to medical centres with oncological services, to cultural with patients resorting to traditional healers) result in a higher fraction of women with more advanced breast cancers in developing than in developed countries. Therefore, making sentinel lymph node biopsy the standard care in developing countries as it is in developed countries [II–31] actually entails a more comprehensive programme, from implementation of nationwide screening for breast cancer to optimizing access to specialized oncological services. On the other hand, these perspectives should stimulate the implementation of associated training programmes, quality assurance, and validation programmes that would eventually result in overall improvements in the general quality of health care.

II–8. Summary

Although the incidence of breast cancer (expressed as age-standardized rate) is almost three-fold higher in developed than in developing parts of the world, this is the most common female cancer in both developed and developing countries. On the other hand, mortality is growing especially in those regions of the world without early detection programmes. Age, family history and genetics, late first pregnancy, and obesity are well-established risk factors for breast cancer. Imaging plays a crucial role for breast cancer screening, for classifying and for defining the extent of breast tumours locally, loco-regionally, and at distant sites.

Most breast cancers are detected by X ray mammography, usually as part of nationwide screening programmes. Ultrasound (US) examination is routinely used as an essential complement to physical examination and mammography in the evaluation of suspicious/equivocal breast masses; US has also become the modality of choice for guiding percutaneous interventional procedures on breast masses, from needle core biopsy to ablation. Magnetic resonance imaging (MRI) with a contrast agent has an important role for identifying mammographically equivocal breast masses as malignant or benign, as well as for defining the local extent of malignant disease.

Besides radiological imaging (mammography, US, MRI), nuclear medicine imaging techniques are playing an increasingly complementary role in the diagnostic characterization of breast lesions, especially when breast-dedicated devices are employed, both for conventional scintimammography and above all for positron emission tomography (PET). Radionuclide procedures play crucial roles for radio-guided surgery in patients with breast cancer, either as radio-guided occult lesion localization (ROLL) or as radio-guided sentinel lymph node biopsy in the phase of primary treatment. Whole-body PET is also of paramount importance for systemic staging, for restaging after neoadjuvant therapy of locally advanced breast cancer, and for assessing the efficacy of anti-tumour therapy.

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Annex III

RADIATION TECHNOLOGY APPLICATIONS IN MINING AND MINERAL PROCESSING

III–1. Introduction

Radiotracers and nucleonic gauges are increasingly being applied by the mining, metallurgy and mineral processing industries for the exploration and efficient extraction of natural resources. Such industries exist in most countries and are often major contributors to national economies. Radiotracers are excellent tools for deriving data in a simple manner from a variety of complex and closed fluidic systems. Various processes, such as grinding, flotation and homogenization, are employed in the mineral processing industries, and vital information can be gathered from these processes for optimal recovery of the ore and extraction of the desired mineral. The information provided by the radiotracers helps with troubleshooting, process control and optimization, investigation of flow patterns, and development and verification of mathematical models.

Geophysical techniques are well established in the oil, gas, uranium, coal and minerals industries. Nuclear borehole logging, which takes advantage of the deep penetration of neutrons and gamma rays, has been widely used in the oil, gas and uranium industries for a long time. Owing to the attractive benefits, the use of radiotracers and nucleonic gauges in such industries is expanding and continuously evolving. New radiotracers, more user-friendly software, and new detectors and data acquisition systems are being developed and introduced.

In addition, various nuclear spectrometry methods have been successfully used for more than 30 years in the field and in industrial environments. Apart from natural gamma radiation measurements for the exploration of radioactive ores, techniques such as gamma ray transmission, gamma ray backscattering, neutron activation analysis (NAA) and its variants (prompt gamma NAA (PGNAA) and delayed gamma NAA (DGNAA)), as well as X ray fluorescence (XRF) are used at various stages in the mining and metallurgy industries. A modern portable nuclear spectrometer enables in-situ analysis resulting in savings in time without compromising on performance, which often matches that of a laboratory instrument.

III–2. Radiotracers, Nucleonic Gauges and Nuclear Analytical Techniques

Radiotracers and nucleonic gauges have been widely used by mining industries to improve the quality of products, optimize processes, and save energy and materials. Many large industries in this field have recognized the high socio-economic as well as technical benefits of radioisotope technology and use such techniques extensively. It is estimated, that a benefit to cost ratio of 40:1 is reasonably achievable.

Nuclear analytical techniques (NATs) for the characterization of materials are based on the utilization of certain properties of the nucleus itself, in contrast to non-nuclear techniques which utilize the properties of the atom as a whole, primarily governed by the properties of electrons in the shells. NATs are frequently associated with the phenomena of ionizing radiation and isotopes. Thus, besides nuclear excitations, nuclear reactions and/or radioactive decay, the processes involved in electron inner shell excitations are also pertinent to NATs. Moreover, some of the NATs of the latter category, such as the synchrotron radiation-induced X ray emission technique can only be performed using nuclear instrumentation, namely various accelerators. Widely used techniques in this category are:

- X ray fluorescence (XRF)
- Ion beam analysis (IBA) techniques, including proton induced X ray emission (PIXE), proton induced gamma-ray emission (PIGE), and Rutherford backscattering (RBS)
- Synchrotron based techniques
- Prompt and delayed gamma neutron activation analysis (PGNAA and DGNAA)

If the cost-effectiveness of radioisotope applications were more widely known, even more industries might use these technologies. Portable nuclear analysis systems, such as portable miniature and compact nucleonic gauges for multipurpose services have been gaining popularity in recent times, especially in the case of a new generation of nucleonic gauges designed and manufactured for elemental analysis in mining industries.

Radiotracers, nuclear analytical techniques and nucleonic gauges can beneficially be used in the mining industries to improve quality and recovery of the mineral from the ore, monitor rapidly the quality of the manufactured product, reduce production downtime, reduce industrial pollution, save raw materials, reduce waste and rejects, reduce labour cost, and make workers' performance easier.

The radiation techniques that are commonly employed in the exploration, extraction and processing of mineral resources are listed in Table III–I.

TABLE III–I. RADIATION TECHNIQUES AND APPLICATIONS IN MINING AND MINERAL INDUSTRIES

Techniques	FIELDS OF APPLICATION					
	LOGGING		MINERAL PROCESSING IN-SITU			
	Delineation of deposit	In-situ assaying	On & off belt analysis	Slurry analysis	Density, weight, level/fill	Elemental composition laboratory analysis
Natural γ radiation	X	X	X	X	X	
γ-ray transmission			X	X	X	
γ-ray backscatter	X	X	X	X	X	
PGNAA & DGNAA	X	X	X			X
XRF analysis		X		X		X
IBA						X
Synchrotron beam analysis						X
PIXE, PIGE analysis						X
RBS						X

III–3. Techniques for Characterization of Minerals

III–3.1. On-line and in-situ analysers

On-line analysers are mainly based on NAA, but XRF portable systems can be used for on-line analysis while logging, as well as for in-situ analysis on samples. XRF based systems have more limitations than neutron based ones because of their geometric requirements and their lower thickness penetration.

Neutron generators, typically of 14 MeV neutrons, are employed to activate samples of coal, cement, etc. on conveyor belts for on-line analysis to determine their elemental composition. Such on-line generators are commercially available from several manufacturers and more than 400 such units are operating in cement factories and other mineral industries. The high throughput and analysis of nearly 90% of the sample are the major advantages of this method compared to conventional sampling methods which cover about 4–10%. Another kind of on-line analyser continuously controls coal quality as it moves through a coal chute in power plants. The oxygen and carbon in the coal are measured based on the fast neutron reaction. Neutrons are thermalized by the large volume of carbon, and thus prompt gamma rays from thermal neutron capture in hydrogen, sulphur and chlorine can also be measured. Delayed gamma rays from radioactive isotopes (such as sodium-24) are also collected. These three types of spectra (gamma rays from fast neutron reactions, prompt gamma rays from the capture of slowed down neutrons, and decay gamma rays) are collected using appropriate time windows. For the gamma detection a scintillator and digital electronics are used. A prototype, installed on a trailer, was recently tried out in Europe using eight loads of different coal samples with a mass of 600 kg each. The compositions were then compared to those from averages of several small samples taken from the load, and analysed with good results.

III–3.2. Off-line analysis

III–3.2.1. Neutrons and ion beam based techniques

In geological prospecting, neutron generator (NG) based NAA is applied by well logging devices for determining the major components in situ. This type of work is usually subcontracted to companies specialized in logging services. It has been shown that NGs can be used for uranium detection using delayed neutron counting.

The sensitivity of NG based activation analysis, when compared to reactor based NAA and other analytical techniques, is limited for on-line applications.

When higher sensitivity is required laboratory instruments and techniques have to be selected.

III–3.2.2. X ray fluorescence based applications

In nearly all geochemical and environmental materials, such as minerals, ores, soils and sediments, many elements are present at levels that can be directly assessed with conventional XRF. The only sample preparation required is usually grinding followed by pelletizing or fusion with a suitable flux, in order to reduce mineralogical effects and improve the accuracy. XRF also continues to be applied to the study of sediments as monitors of heavy metal pollution in water.

XRF has great potential in the field of geochemistry. The possibility of tuning the photon energy to optimize the excitation of specific elements and suppress the excitation of others can be very useful, for example in the detection of noble metals in minerals. The non-destructive character and high penetration power of both the excitation and the fluorescence X rays makes micro-synchrotron radiation-XRF (micro-SR-XRF) ideal for analysing unopened fluid inclusions in minerals. The composition of the fluid inclusion can reveal information on conditions during mineral genesis of basic geological interest, but also on the conditions for the formation of economically important ones.

Currently, one of the most widely-used applications of portable XRF instrumentation is for assessing the environmental impact of lead contamination in soil. In the case of contaminated land, the main benefit of portable XRF instrumentation is that detection limits are 5 to 10 times lower than ‘permissible’ limits for lead in soil. For many of the other toxic metals of environmental interest, although the detection limits of portable XRF are not adequately sensitive for the purpose of qualifying the samples as safe, they could still be used for estimating gross contamination.

III–3.2.3. Synchrotron based applications

During the past decade, synchrotron techniques have found a wide range of applications in the field of environmental monitoring, particularly related to the management of mine tailings. Straightforward yet powerful techniques such as X ray absorption spectroscopy (XAS) and X ray diffraction (XRD) can provide detailed information about elemental concentrations and mineral composition, including speciation, without the need for complicated and potentially unreliable sample preparation. Examples include the analysis of arsenic, selenium and chromium, where speciation measurements are vital. Other examples include the assessment of airborne pollution, such as that from sulphur, lead and nickel, that can result from smelting processes.

Great advances are being made in using synchrotron radiation, partially due to the presence of reliable XAS and XRD beam lines in existing synchrotron facilities, which are typically in very high demand. Improved detectors have resulted in better detection limits, and the basic research is resulting in proven data analysis methods. These developments have occurred at a time of growing concern about the legacy of worldwide mining operations. Governments are having to deal with abandoned mine sites, and mining companies are increasingly focused on improved extraction and processing technologies that will lower environmental impacts.

To give a specific example, the industrial science programme at the Canadian Light Source has been highly successful in engaging mining companies to use synchrotron techniques for issues related to mine waste management and airborne pollution. The rapid growth of research in this area may soon lead to the development of an international research centre focusing on environmentally sustainable mining.

III–4. Case Studies on Radiotracer Applications in Mineral Processing

Brief descriptions of radiotracer studies conducted in Member States for troubleshooting in their industrial sectors are given below to illustrate the benefits of these applications.

III–4.1. Radiotracer investigation of leaching process in a gold processing plant in Ghana

In 2009, a radiotracer study was carried out at a gold processing plant (Fig. III–1) in Ghana to estimate the residence time distribution (RTD) in the

FIG. III–1. Gold processing plant where a radiotracer was used to investigate the flow

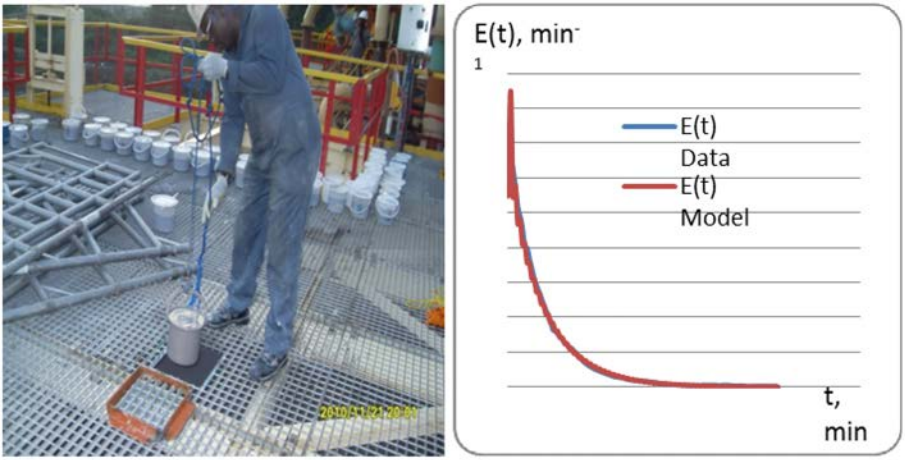

FIG. III–2. Experimental RTD sampling and modelling.

leaching tank using an iodine-131 radiotracer with the aim of increasing the leaching efficiency.

The shape of the experimental RTD (Fig. III–2) curve indicated that the flow behaviour in the tank was close to that of an ideal mixer. Modelling of the experimental data, however, revealed that the tank was not behaving as a single perfect mixer but consisted of two mixing zones, corresponding to regions of vigorous mixing (75%) and pockets of stagnant zones (25%), indicated by the unusual long tail in the RTD curve. Stagnant zones decrease productivity as dissolved gold can be trapped in them. Based on these radiotracer results, the slurry homogenization within the tank was remediated and an increase in gold recovery by a few percentage points was achieved.

III–4.2. Radiotracer investigation of the grinding process in a copper processing plant in Chile

Radiotracer studies were carried out during a recently completed coordinated research project in a copper mining plant in Chile to characterize the fluid dynamic behaviour of three mills of the regrinding circuit (Fig. III–3) in the concentrator plant. Fine and coarse tailings from the plant were activated with neutrons in the nuclear reactor of the Chilean Nuclear Energy Commission and used as radiotracers to study the granulometry of the tailings while bromium-82 as potassium bromide (KBr) was used as the tracer to study liquid flow. The radiotracer was injected into the feed flow and was measured in the outputs of each circuit in real time.

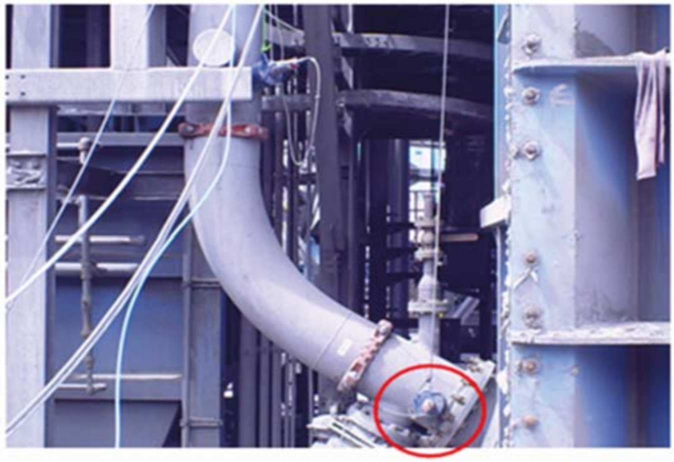

FIG. III–3. Experimental RTD measuring point.

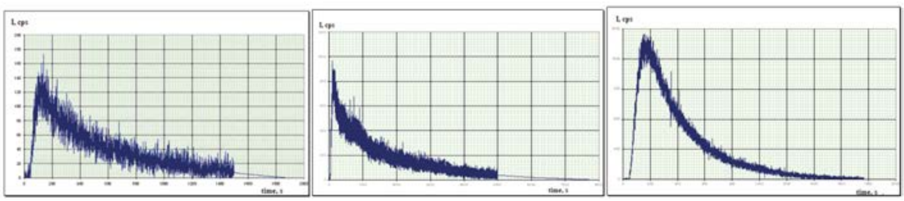

FIG. III–4. Experimental RTD curves for fine and coarse tailing grains, as well as for liquid phase.

The experimental RTD curves (Fig. III–4) showed different flow patterns for fine, coarse and liquid phases; the respective mean residence times (MRTs) through the mill system were found to be 386 seconds, 1693 seconds and 407 seconds, which indicate a relatively low performance of the grinding system. These studies helped the authorities to plan appropriate action such as modifying the design of the system.

III–5. Portable Nuclear Analysis Systems for Borehole Logging

Among the many physically different borehole logging techniques, nuclear borehole logging is practically the only one that has the capacity for providing quantitative in-situ mineral quality information in real time. Nuclear borehole logging, apart from its capacity to deliver data instantaneously, also has the advantage that the highly penetrating gamma and/or neutron radiation effectively analyses much larger sample volumes than either percussion or core drill samples.

Nuclear borehole logging techniques involve detection and measurement of radiation, which may be counted as accumulated radiation or could be processed further to obtain the radiation energy distribution. These two approaches to data acquisition result in spectrometric and non-spectrometric (total count) logging, respectively.

III–5.1. Low activity gamma spectrometric borehole logging probe for coal delineation and coal raw ash content

Gamma spectrometric bore hole logging yields very useful information in the coal mining industry. Most commercially available logging technologies for the coal mining industry are non-spectrometric (i.e. measure all the gamma radiation received without discrimination in energy). Non-spectrometric gamma–gamma (i.e. gamma ray backscattering) and natural–gamma (i.e. direct measurement of natural gamma radiation) techniques are now being used routinely for the delineation of coal and mineral seam sediments. The coal seams are easily identifiable in the gamma–gamma logs because of the difference in density between coal and sediments.

This approach is satisfactory for the delineation of the roof, floor and thickness of a coal seam. However, it does not always provide an accurate measurement of the ash content in coal seams. This is because the correlation between ash and coal density is not always high. While coal deposits do exist where there is a high correlation between ash content and density, in most deposits there are significant fluctuations in this relationship due to the non-uniform chemical composition of ash in coal and variations in other physical properties of the coal, such as rank and porosity. Only spectrometric techniques can provide direct and accurate estimations of ash content, and its elemental constituents, in coal.

The majority of nucleonic gauges apply substantial radioisotope activity, but there are a number of ingenious small nucleonic gauges using low radioactivity sources of under 3.7 MBq. This activity is defined in some countries as the minimum activity of a radioactive source requiring a licence for possession, use and transport of radioactive substances. These gauges are currently being implemented for several industrial applications in Australia and Japan.

Low radiation intensity (1.1 MBq) gamma spectrometric borehole logging probes (Fig. III–5) for coal delineation and coal raw ash content utilize single-scattered gamma rays to provide information about the bulk density of the formation, and multi-scattered rays of lower energies to determine coal raw ash content.

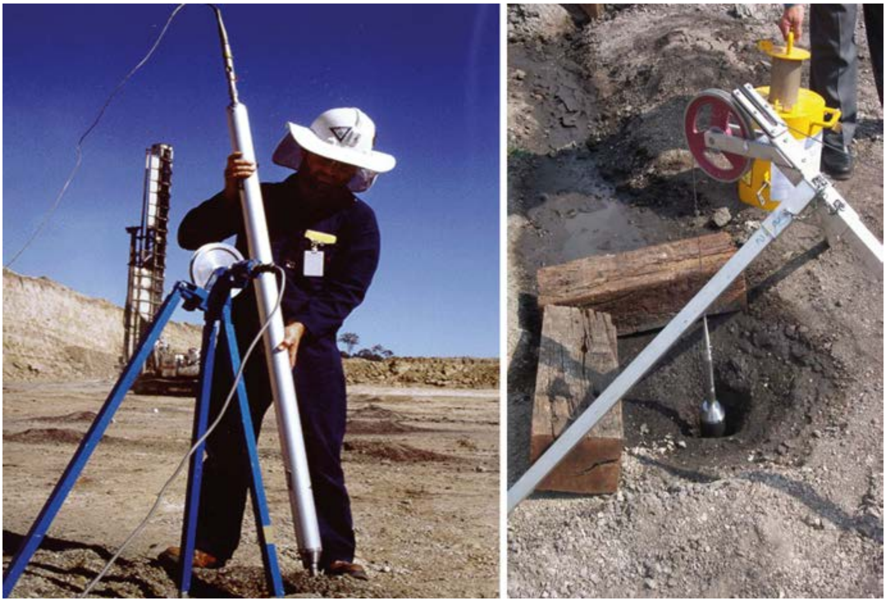

FIG. III–5. Low radiation intensity (1.1 MBq) gamma spectrometric borehole logging probe for coal delineation and coal raw ash content.

III–5.2. PGNAA borehole logging for copper grade analysis in Chile

The PGNAA technique was initially developed for off-line applications but has recently been used for on-conveyor belt analysis and borehole logging. When a thermalized, or slow, neutron comes close enough to a nucleus, it will be absorbed by that nucleus. This absorption process causes the nucleus to become excited, a condition that is relieved by the nearly instantaneous release of a unique set of gamma ray energies. Californium-252 is mostly used as a neutron source together with thallium doped sodium iodide (NaI(Tl)) or bismuth germinate (BGO) scintillation detectors. The PGNAA technique is applied successfully both in borehole logging and processing of various minerals.

The PGNAA technique is well suited for many mining applications and has two major advantages over the conventional X ray fluorescence technique: the deep penetrating ability of the neutrons and gamma rays allows full measurement of material on a conveyor belt or in a chute or a bucket, whereas X rays penetrate so little that their analysis is strictly a surface phenomenon; and PGNAA can detect many light elements (e.g. Si, Al, K Na, Mg, P and S) which XRF cannot in on-line applications.

FIG. III–6. PGNAA borehole logging for copper grade analysis in Chile.

Figure III–6 shows the borehole logging process for copper ore analysis in the Chuquicamata (Chile) open cut copper mine using a PGNAA probe.

The PGNAA measured a copper content lower than 1% with 10% accuracy. Using this technique, a new estimation of copper reserves was conducted in Chile which kindled interest in the industry in processing the relatively low grade copper mineral ore.

III–5.3. PGNAA for elemental analysis of raw materials in cement processing in Thailand

The main requirement for a modern cement processing plant is prompt (less than 10 minutes) and accurate analysis of various elements that move on belt conveyors. This can be achieved only with PGNAA, which uses a californium-252 neutron source and BGO scintillation detectors to determine elemental composition based on thermal neutron capture gamma rays.

The PGNAA technique is typically used in modern cement plants for pre-blending optimization as well as raw mix optimization processes. This means that PGNAA equipment replaces huge silos. Despite its relatively high price the initial cost is paid back in a few months. Further benefits include an increase in quality and in quantity bringing additional incomes of millions of dollars a year.

Figure III–7 shows the schematic design of two PGNAA crossbelt analysers in a big, modern cement plant in Thailand. The system, called the 'Raw Mix Optimization System (RAMOS)' has been performing well for the past five years. It is used to determine the composition of both raw and mixed materials before kilning. It works automatically on the conveyor belt. It is accurate, saves time and has lower operational costs in comparison to conventional methods that use silos and conduct sampling and chemical analysis in a laboratory.

The PGNAA technique is well established in on-line cement, coal ash and mineral ore analyser systems. The next generation of PGNAA analysers will

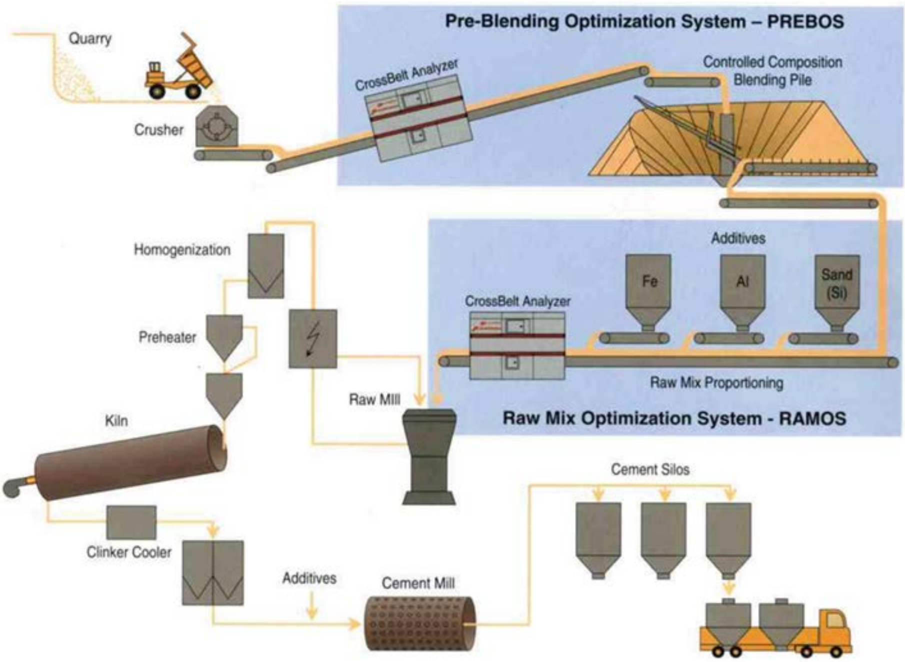

FIG. III–7. The schematic design of PGNAA equipment in a cement plant in Thailand.

greatly benefit from neutron generators due to their superior life cycle economics and versatility.

III–6. Synchrotron Applications for Assessing Arsenic in Soils and Mine Tailings in Former Industrial Sites in Northern Canada

Synchrotron-based techniques, in particular X ray absorption spectroscopy (XAS), are powerful tools to enhance our understanding of the geochemistry of mine waste. Owing to its toxicity, arsenic has drawn worldwide attention in recent years over environmental and health concerns. Arsenic levels in the aquatic environment can be elevated by geological processes such as mineral weathering and dissolution, or more importantly by anthropogenic activities in particular mining and smelting activities. Thus it is important to investigate arsenic-bearing phases with respect to their concentrations, distribution, speciation, mobility and stability.

Arsenic is a natural element that can be found distributed throughout the Earth's crust, either alone or along with ores of minerals such as uranium and gold. For example arsenopyrite, an ore of arsenic, is a rock in which gold is often

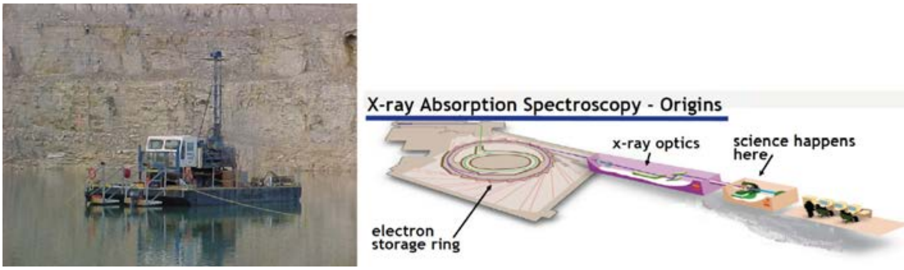

FIG. III–8. Left: A barge mounted drill rig at the mine site was used to sample pore waters and to obtain cores of the tailing material. Right: X ray absorption experiment schematic design at the synchrotron facility.

embedded. Some uranium ores contain significant amounts of arsenic. It is therefore important to monitor arsenic levels as well as its speciation in the effluents and tailings from mining sites which use such ores, in order to ensure that the arsenic does not find its way into the food chain or potable water. X ray absorption fine structure (XAFS) spectroscopy is one of the few techniques that can be used to identify and quantify metal and metalloid species, such as the arsenic species, in complex solid mixtures; the principles of the technique and its benefits/drawbacks have been described in numerous publications. Over the past decade, XAFS spectroscopic studies have been used for the quantification of various chemical species of arsenic.

The mining of the high-grade uranium deposits located in northern Saskatchewan, Canada, accounts for approximately one-third of the world's total uranium production. Along with uranium, arsenic co-mineralization is present and the amounts are significant in the ore from some deposits. In a typical acid leach uranium ore processing facility, most of this arsenic is leached into solution. Following uranium removal by solvent extraction and precipitation processes, the arsenic remains in an acidic sulphate waste solution referred to as raffinate. The raffinate is then subjected to a lime neutralization process where arsenic is removed by precipitation with ferric iron, thereby producing low solubility iron–arsenates. After neutralization, the tailings are placed in a tailings disposal facility. A potential concern is about the soluble arsenic originating from the neutralized raffinate solids in the water of the final tailings.

Through a systematic XAFS structural study on the iron (III)-arsenate precipitates obtained by the neutralization of the process effluent from the above-mentioned uranium mines, it could be established that with time arsenic was getting transformed to the least soluble state As(V), which is desirable.

Figure III–9 presents the results of an assessment of the stability and long term fate of mill tailings, indicating that the disposal of arsenic in the mine

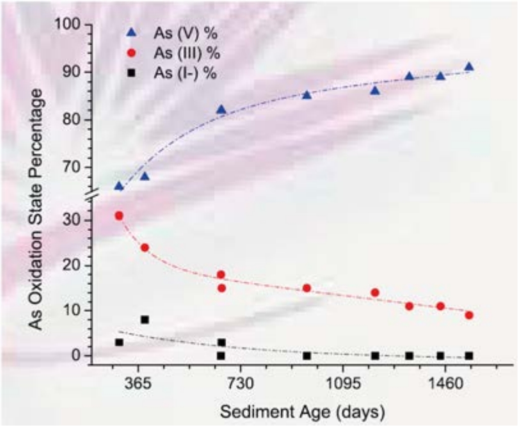

FIG. III–9. Over four years of exposure in the tailing management facility environment a trend can be clearly seen in the three solid phases of arsenic (black, red and blue data points). Both arsenide (As(I), black) and arsenite (As(III) red) phases show decreases over time with a simultaneous increase in the As(V) oxidation state (blue).

tailings as amorphous ferric arsenate would result in the conversion of >90% arsenic to the preferred As(V) state over a period of 4 years, which is one-sixtieth as toxic as As(III) and much less mobile in groundwater.

These investigations show that XAFS is a useful tool to probe the arsenic local structural environment in an amorphous material such as amorphous ferric iron-arsenate co-precipitate. XAFS has provided direct local structural evidence of the transformation of amorphous scorodite to crystalline scorodite through the ageing process, which is of potential environmental significance.

III–7. Conclusion

A wide range of techniques and technologies that employ radioisotopes or radiation sources offer great advantages to the mining industries, be it for exploration, optimization of processes, troubleshooting, assessment of mining sites or ensuring environmental protection. This is evident from the increasing use of such technologies by the mining industries and the continuous evolution, innovations and improvements in the techniques and instruments used.

Annex IV

TECHNOLOGY OPTIONS FOR A COUNTRY'S FIRST NUCLEAR POWER PLANT

Several Member States of the Agency are considering introducing nuclear power to their energy mix for the first time. Although various technology options are available to these countries, selecting the most suitable nuclear reactor design requires not only a careful understanding of existing designs but also in-depth knowledge of country-specific needs, conditions and other considerations. To make an informed decision, the key characteristics of a particular nuclear project must be clearly understood and specified from the outset and balanced, comprehensive and up to date information about reactor designs, concepts and fuel cycle options must be made available and evaluated. This document details important considerations to be taken into account when selecting a reactor design for a country's first NPP and provides information on technology options available to newcomer countries, listing potential designs and describing their key characteristics.

IV–1. Some Considerations When Selecting the First Nuclear Power Plant

Some elements are of key importance when narrowing down potential nuclear reactor designs to be selected. These include the size and stability of the national electricity grid, the seismicity of the selected site, the availability of water resources for ultimate cooling and the accessibility to waterways or other appropriate transportation routes for the transportation of large components or modules. Therefore, it is important for prospective NPP owners to examine these elements in some detail in order to clearly establish the boundary conditions in the technology assessment process.

The desired level of technological maturity or innovation in the new NPP design is another decision which has to be made early. Structures, systems and components (SSCs), and design and analysis methods and techniques which involve characteristics, materials, manufacturing processes, working conditions and plant environment conditions that are identical or similar to those that have been operated or applied successfully in existing NPPs, preferably over a span of several years, are referred to as 'proven technology'. Each country needs to balance the benefits and the challenges associated with the selection of a design of a specific level of technological maturity. Some countries may prefer to use the deployment of a new nuclear power programme as an opportunity to develop national capabilities in several key areas associated with these advanced reactor designs. This is usually done through comprehensive technology transfer arrangements with the supplier, where a newcomer country may initially pursue a ‘turnkey approach’ (following the lead of the supplier country) but would increasingly take on larger and more significant roles in future nuclear projects. Each country needs to strategically evaluate the technological maturity risk they are willing to assume and weigh it against the potential gains in national capabilities associated with innovation and technology transfer.

The level of completion of a design and its licensability in the new hosting country are also important considerations. Choosing a nuclear reactor design that is finalized and frozen, particularly one that has undergone licensing review in other countries, can minimize project uncertainties. While some modifications may be needed due to local regulatory requirements or due to the special characteristics of a site, a complete design helps to ensure that the project will be within budget and schedule.

On some occasions, striking a balance between the use of a large, inexpensive local labour force applying traditional construction techniques on site and the use of advanced construction techniques that may require the procurement of module fabrication facilities (i.e. a ‘modular approach’) or sophisticated machinery is also important. A cost–benefit analysis would enable a country to assess whether the increase in construction time when using traditional construction techniques will be offset by the increase in cost associated with the use of more advanced construction techniques.

Performance-specific considerations of a given design, such as operability, manoeuvrability, inspectability, maintainability, availability factor and reliability, are of course also of paramount importance and careful evaluations of each one of those characteristics should be carried out.

Furthermore, it may be of interest to examine the technology options that are being selected in other countries in the same region, since establishing productive regional partnerships would enable efficiencies in areas such as operating experience, spare parts inventories, enrichment and fuel fabrication services, waste and spent fuel management facilities, etc. Similar efficiencies could be achieved by selecting a widely used reactor design and by participating in the ‘owners’ group’ for that design. It is generally recommended that newcomer countries consider both types of partnerships, in particular with more experienced countries or operators. As an additional benefit, these may increase negotiating strength when dealing with suppliers.

Last but not least, other key factors in choosing a nuclear reactor design include fuel procurement and spent fuel and waste management. With regard to fuel, the availability of several competitive suppliers for the various raw materials and services needed to produce the nuclear fuel required for a given reactor design, such as the procurement of the fissionable raw material, enrichment

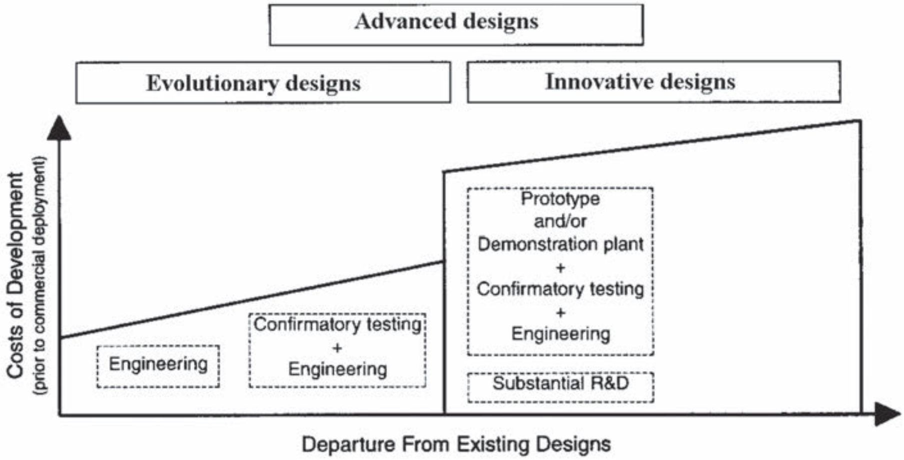

FIG. IV–1. Classification of advanced reactor designs.

services, and fuel fabrication, should also be considered. As for spent fuel and waste management, long term plans are needed.

IV–2. Classifications of Reactor Designs

There are various categorizations for nuclear reactor designs. For example, advanced NPP designs are defined as those designs of current interest for which improvements over their predecessors and/or existing designs are expected (Ref. IV–1). Depending on the number of modifications implemented, advanced reactor designs can be divided into 'evolutionary' and 'innovative' (Figure IV–1). An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining the essentials of the proven design to minimize technological and investment risks. The development of an evolutionary design requires, at most, engineering and confirmatory testing. An innovative design is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial research and development (R&D) efforts, feasibility tests, and a prototype and/or demonstration plant are probably required prior to the commercial deployment of this type of design.

An alternative classification was developed by the Generation IV International Forum (Ref. IV–2), which divided nuclear reactor designs into four generations. The first generation consisted of the early prototype reactors of the 1950s and 60s. The second generation is largely made up of the commercial NPPs built since the 1970s which are still operating today. The Generation III reactors were developed in the 1990s and include a number of evolutionary designs that offer improved safety and economics. Following the increased interest in nuclear power seen in the first decade of the 21st century, additional improvements are being incorporated into Generation III designs, resulting in several concepts that are actively being developed and being seriously considered for near term deployment in various countries. Beyond 2030, it is anticipated that new reactor designs will address key issues such as closing the fuel cycle or enhanced proliferation resistance at the same time as competitive economics, safety and performance. This generation of designs, Generation IV, consists of innovative concepts where substantial R&D is still needed. However, it should be noted that there is no precise and generally accepted definition of each generation.

In addition, nuclear reactors have traditionally been classified depending on their neutron spectrum, or depending on the coolant they use to extract the fission energy from the core. According to the first criterion, reactors can be described as 'thermal' when they use low energy neutrons and as 'fast' when they use much higher energy neutrons that are not slowed down by a moderator. According to the latter criterion, reactors can be classified as water cooled reactors (WCRs), gas cooled reactors (GCRs), liquid metal cooled reactors (LMRs) and molten salt cooled reactors (MSRs). Furthermore, the WCR category can be subdivided into boiling water reactors (BWRs) — where the core is at relatively low pressure and the coolant is allowed to boil — and pressurized water reactors (PWRs) — where the core is at high pressure and the coolant remains a liquid. The WCR category can also be subdivided into light water reactors (LWRs) and heavy water reactors (HWRs) that use deuterium water. While most HWRs belong to the PWR type and are also referred to as pressurized heavy water reactors (PHWRs), some advanced designs use the BWR concept. Several advanced designs are referred to as 'integral designs', that is, designs in which the whole reactor primary circuit (including, for instance, the pressurizer, coolant pumps, and steam generators/heat exchangers, as applicable) is enclosed in the reactor vessel. Finally, depending on the size of the plant, nuclear reactors can be classified as 'small' (with an output of less than 300 MW(e)), 'medium' (between 300 and 700 MW(e)) and 'large' (more than 700 MW(e)). In general, although innovative reactor designs do not always fit this norm, we can say that most WCRs and GCRs are thermal reactors, while most fast reactors are cooled by liquid metals.

Various organizations, including design organizations, utilities, universities, national laboratories and research institutes, are involved in the development of advanced NPPs featuring evolutionary and innovative reactor designs. Since evolutionary designs are the most likely candidates to serve as the basis for a first NPP in most countries, the remainder of the document will examine only these.

IV–3. Trends in Evolutionary Reactor Designs

Evolutionary reactor designs focus on improving the economics and the performance of existing designs while at the same time meeting even more demanding nuclear safety requirements. Although efforts have also been made to optimize the use of fissionable materials and minimize the production of spent fuel and nuclear waste, the full closing of the nuclear fuel cycle is to be expected only once NPPs based on innovative reactor designs are brought into operation.

The following trends in the design of evolutionary reactors can be observed.

Firstly, there is a trend towards reducing the overall capital cost of a new NPP by reducing and simplifying plant systems and components; developing standardized designs that need to be validated and licensed only once; using advanced construction technologies and management practices that shorten the construction schedule and improve the quality or by incorporating modularity in the design, which enables factory pre-fabrication of both structural and system modules. Most evolutionary designs also include design features that allow for plant lifetimes of 60 years and longer. Taking advantage of economies of scale by designing larger reactors (capital costs are amortized faster due to higher electricity production) can also help reduce overall capital costs. On the other hand, in recent years a parallel trend emphasizing the affordability of NPPs has arisen, resulting in the development of small or medium size reactors that can be built in a phased manner up to the total desired power according to the owner's financial means. These smaller designs may also be ideal for newcomer countries with small electricity grids and limited financial resources.

The second trend is towards lowering operating costs through the optimization of the fuel cycle. Savings result from increased plant availability, more effective use of fissionable resources and minimization of waste and spent fuel quantities and management costs. Efforts have also been made to attain higher thermal efficiencies by using advanced turbines and sophisticated thermodynamic cycles, as well as expanded non-electrical applications.

The third trend is towards improved performance, by various means, including the use of smart components that monitor their own performance and warn operators about incipient failures; in-service testing and maintenance; relying on probabilistic risk assessment methods and databases that allow designers to focus design efforts on the systems and components with higher risk of failure; or using digital instrumentation and control (I&C), as well as improved human–machine interfaces that significantly reduce human errors. Better knowledge of underlying phenomena and better technology mean that the margins needed to accommodate unknowns can be reduced in new designs. Furthermore, since these designs are expected to operate under higher demands, they also use improved corrosion resistant materials.

Lastly, another key design improvement is the use of passive safety systems that rely on gravity and natural convection, as well as temperature and pressure differentials, enabling these systems to function without electrical power and/or actuation by electrically powered I&C systems. Furthermore, many evolutionary designs have been developed based on ‘user requirements’, that is, the lessons learned from the operation of the existing fleet of NPPs.

IV–4. Evolutionary Designs and Their Key Characteristics

A publication providing technical guidance and a design-neutral systematic approach to evaluate the technical merits of the various NPP technologies available on the market, based on each country’s needs and requirements, is being developed by the Agency. In addition, Member States can obtain up to date information about advanced reactor designs and concepts — from evolutionary WCR designs for near term deployment to innovative reactor concepts still under development — through the Agency’s web-based Advanced Reactors Information System (ARIS).[1]

Table IV–1 summarizes all evolutionary reactor designs for which information has been made available to the Agency through the development of ARIS, through the Agency’s relevant technical working groups and from the open literature. The designs are arranged in descending order of electrical output. A brief summary of some key features of each one of these designs can be found after Table IV–1.

The designs listed in Table IV–1 are briefly described hereafter, in alphabetical order. The advanced boiling water reactor (**ABWR**), available from two competing vendors (GE-Hitachi and Toshiba), combines BWR design features from Europe, Japan and the USA. Developed in direct response to the Electric Power Research Institute’s (EPRI’s) *Utility Requirements Document* (Ref. IV–5), the ABWR is licensed in Japan, the USA[2], and it is the first evolutionary reactor design to operate commercially. Currently four ABWRs are in operation in Japan (Kashiwazaki-Kariwa 6 & 7, Hamaoka-5 and Shika-2), and two are under construction there.[3] Several more are planned in both Japan and the USA. Therefore, this design has a proven capital, operation and maintenance cost structure. Taking advantage of existing prefabricated construction experience and applying it to a modularized design, the ABWR was designed with a shorter construction schedule in mind. Although existing ABWRs have a capacity of

[1] See Reference IV–4.

[2] In addition, it is licensed in Taiwan, China.

[3] Two ABWRs are also under construction in Taiwan, China.

TABLE IV–1. REACTOR DESIGNS AVAILABLE FOR NEAR- AND MID-TERM DEPLOYMENT

Name	Type	Designer	Power [MW(e)]	Status[a]
ABWR-II	BWR	GE Hitachi	1700	Basic design
APWR	PWR	MHI	1540–1700	Detailed design
EPR	PWR	AREVA	1600+	Under construction
ESBWR	BWR	GE Hitachi	1550	Detailed design
ABWR	BWR	GE Hitachi, Toshiba	1350–1500	In operation
APR-1400	PWR	KHNP	1400	Under construction
KERENA	BWR	AREVA+E.ON	1250+	Basic design
ACR-1000	PHWR	AECL	1200	Detailed design
WWER-1200	PWR	Gidropress	1200	Under construction
ATMEA1	PWR	ATMEA	1100	Basic design
WWER-1000	PWR	Gidropress	1000	In operation
AP1000	PWR	Westinghouse	1000	Under construction
BN-800	SFR[a]	Rosenergoatom	880	Under construction
mPower	Integral PWR	B&W	180–360	Conceptual design

TABLE IV–1. REACTOR DESIGNS AVAILABLE FOR NEAR- AND MID-TERM DEPLOYMENT (cont.)

Name	Type	Designer	Power [MW(e)]	Status[a]
EC6	PHWR	Candu Energy Inc.	740	Detailed design
ACR-1000	PHWR	Candu Energy Inc.	1200	Basic design complete
Indian PHWR-220	PHWR	NPCIL	220	In operation
Indian PHWR-700	PHWR	NPCIL	700	Under construction
Indian PHWR-540	PHWR	NPCIL	540	In operation
PFBR	SFR	IGCAR/BHAVINI	500	Under construction
IMR	Integral PWR	MHI	350	Conceptual design
IRIS	Integral PWR	International Consortium	100–335	Basic design
SMART	Integral PWR	KAERI	330 MW(t)/100 MW(e)	Detailed design
AHWR300-LEU	Boiling HWR	BARC	300	Basic design
CAREM-25	Integral PWR	CNEA	27	Under construction
NuScale	Integral PWR	NuScale	45–540	Basic design
KLT-40S	Floating PWR	OKBM	35	Under construction
SVBR-100	Lead-Bismuth FR	AKME Engineering	100	Detailed design

TABLE IV–1. REACTOR DESIGNS AVAILABLE FOR NEAR- AND MID-TERM DEPLOYMENT (cont.)

Name	Type	Designer	Power [MW(e)]	Status[a]
4S	SFR	Toshiba	10	Conceptual design
ACP-100	PWR	CNNC	100	Detailed design
ACP-600	PWR	CNNC	600	Detailed design
ACP-1000	PWR	CNNC	1000	Detailed design
ACPR-1000	PWR	CGNPC	1150	Detailed design

[a] Status descriptions can be found in *Terms for Describing New, Advanced Nuclear Power Plants* (IAEA-TECDOC-936, Vienna, April 1997) (Ref. IV–1).

[b] Sodium cooled fast reactor.

1370 MW(e), future ABWRs are expected to reach 1500 MW(e) due to an existing reactor core margin for uprates. The ABWR has fully digital I&C and has adopted reactor internal pumps that eliminate the need for large external recirculation coolant loops and make it possible to maintain core coverage during a postulated loss of coolant accident (LOCA). Significant efforts have also been made in the design of the ABWR to improve its safety systems and reduce the core damage frequency to very low values. Features have been included to mitigate severe accidents and to reduce the off-site consequences of accidents, and its containment vessel is made of reinforced concrete with an internal steel liner.

The **ABWR-II**, developed by GE-Hitachi, is a further enhancement of the ABWR. It offers a larger power output of up to 1700 MW(e), due to a larger core (with 1.5 times larger fuel bundles) and the control rods arranged in a K-lattice (as opposed to the conventional N-lattice). This new core design may also provide increased flexibility in terms of higher burnup, use of mixed oxide (MOX) fuel and higher conversion rate configurations. The ABWR-II also includes a modified emergency core cooling system and a combination of active and passive heat removal systems designed for improved economics, performance and safety.

The **ACP100**, a multipurpose small module reactor developed by the China National Nuclear Corporation (CNNC), is a 100 MW(e) advanced pressurized water reactor with small integrated modules. Its 2-6 modules can be built at the same time and a single module of the ACP100 can supply 310 MW(th) of Reactor thermal power, a maximum heat production of 1000 GJ/h, a maximum steam production of 420 t/h and a maximum seawater desalination production of 120 000 t/d.

The **ACP600** is a 600 MW(e) two-loop advanced PWR developed by CNNC. The reactor core contains 121 fuel assemblies, with decreased core linear power density supplying higher thermal margin. Passive safety systems are employed in addition to active safety systems, enhancing the response capability in the case of a station black out accident.

The **ACP1000,** also developed by CNNC, is an 1100 MW(e) three-loop advanced PWR. The reactor core of this advanced light water reactor is composed of 177 advanced fuel assemblies, increasing power while ensuring a sufficient thermal safety margin. Both active and passive safety systems were adopted in the ACP1000 design to perform functions such as emergency core cooling, core residual heat removal, melt core retaining and cooling, and containment heat removal. It also contains enhanced protection for external hazards. It also offers an extended plant design lifetime (60 years) and refueling cycle (18 months) for an improved economic competitiveness.

The **ACPR1000** is an advanced Chinese 1000 MW(e) PWR nuclear reactor developed by CGNPC. This 3-loop PWR, with a generator output of around 1150 MW(e), focuses on safety performance while maintaining consideration for economic efficiency. Enhanced safety features include an extra heat removal system to remove the heat out of the containment through containment spray and to realize in-vessel retention (IVR) of core damage under severe accident by external reactor vessel cooling (ERVC).

The advanced CANDU reactor-1000 (**ACR-1000**), developed in Canada, is a 1200 MW(e) pressure tube reactor that retains many essential features of a typical CANDU plant design, including a core with a horizontal fuel channel, a low temperature heavy water moderator, a water filled reactor vault, two independent safety shutdown systems, a highly automated control system, on-power fuelling and a reactor building that is accessible for on-power maintenance and testing. Key differences incorporated into the ACR-1000 are the use of low enriched uranium fuel (as opposed to natural uranium), the use of light water instead of heavy water as the reactor coolant, and a lower moderator volume to fuel ratio. The phase 2 pre-licensing review by the Canadian Nuclear Safety Commission has been completed.

The Indian advanced heavy water reactor (**AHWR**) is a 300 MW(e), vertical pressure tube-type, heavy water moderated, boiling light water cooled reactor. It has been designed to achieve large-scale use of thorium for the generation of commercial nuclear power. It will produce most of its power from thorium, with no external input of uranium-233 in the equilibrium cycle. The reactor incorporates a number of passive safety features and is associated with a closed fuel cycle with the objective of reducing its environmental impact. In addition, several features have been incorporated that are likely to reduce its capital and operating costs.

The Westinghouse advanced passive PWR (**AP1000**) is a two-loop 1100 MW(e) PWR, scaled up from the AP600 design already certified in the USA, which was originally compliant with EPRI's *Utility Requirements Document* (Ref. IV–5). In the AP1000, designers have made an effort to simplify all systems and to reduce the number of systems and components for easier construction, operation and maintenance. Like other evolutionary concepts, the AP1000 uses prefabrication and modular construction with the objective of reducing construction schedule uncertainties. One of the signature characteristics of the AP1000 is the use of passive safety systems which require no outside electricity or operator action for 72 hours. On the other hand, the plant design utilizes proven technology and capitalizes on more than 40 years of PWR operating experience. The AP1000 also incorporates features designed to mitigate severe accidents, such as in-vessel retention of core debris following a core melt event, and no reactor vessel penetrations below the top of the core level.

Two AP1000 projects (four units in total) are currently under construction in China (Haiyang and Sanmen) and substantial construction and operating experience is expected to be gained from these. In the USA, final certification by the US Nuclear Regulatory Commission (USNRC) for the amended AP1000 design is expected, and three engineering, procurement and construction contracts for the Vogtle, Summer and Levy sites were signed.

The advanced power reactor 1400 (**APR1400**), with a rated power of 1400 MW(e), is the largest two-loop PWR currently available. It was developed in the Republic of Korea, based on accumulated experience from the design and operation of the 1000 MW(e) OPR 1000 and from EPRI's *Utility Requirements Document* (Ref. IV–5). The APR1400 incorporates a number of changes in response to operators' needs for enhanced safety, performance and economics and to address new licensing requirements such as the mitigation of severe accidents. It has a very characteristic configuration, with two large steam generators and four reactor coolant pumps in a 'two hot legs and four cold legs' arrangement. The APR1400 also features fully digital I&C, and a main control room designed with full consideration of human performance capabilities (or, as these are generally referred to, 'human factors'). Incorporating safety systems with both active and passive characteristics, the APR1400 has also been designed to take advantage of modularization and prefabrication construction techniques designed to make the construction budget and schedule more predictable. Four APR1400 units are currently under construction in the Republic of Korea at Shin-Kori 3 & 4 and Shin-Ulchin 1 & 2 and are expected to enter commercial operation in 2013–14 and 2015–2016, respectively. The APR1400 has also been selected for the first four units that will be built in the United Arab Emirates.

The advanced pressurized water reactor (**APWR**) is a four-loop PWR developed jointly by a group of Japanese utilities, Mitsubishi Heavy Industries (MHI) and Westinghouse that relies on a combination of active and passive safety systems. The high capacity APWR, with 1500 MW(e) (1700 MW(e) in Europe and the US), takes advantage of economies of scale and uses high performance steam generators and low pressure turbines with very large last stage blades. The APWR allows operation with long fuel cycles and increased flexibility such as the use of low enriched fuel in order to reduce uranium requirements and the use of MOX cores and high burnup fuels. A neutron reflector is used with the objective of improving the neutron economy and the long term reliability of the reactor vessel. The container includes a steel liner intended to prevent leakage, surrounded by the concrete structure that provides structural protection. As in other evolutionary designs, the construction of the APWR also takes advantage of modularization and advanced design, simulation and management computer programmes.

ATMEA1, developed by Japan and France, brings together technology that is already incorporated into AREVA's EPR (see below) and MHI's APWR (described above). A three-loop PWR that relies primarily on active safety systems, it incorporates severe accident mitigation features. ATMEA1 will be able to operate using a full core of MOX fuel.

The 880 MW(e) **BN-800** sodium cooled fast reactor design is the logical development of the BN-600 reactor design. BN-600, the world's only commercial fast breeder reactor in operation, has been operating since 1980 at the Beloyarsk NPP site in Russia. The experience gained during the BN-600 reactor operation has led to new design features in the BN-800 reactor, as well as to enhanced safety characteristics. Of these, the most important are the adoption of one turbine; steam instead of sodium reheating; the introduction of a special decay heat removal system that dissipates the heat through 'sodium–air' heat exchangers connected to the secondary circuit; the adoption of a core catcher for collecting core debris in the case of core melting and of a special sodium cavity located above the core to reduce the sodium void reactivity effect; and the inclusion of an additional passive shutdown system with hydraulically suspended absorber rods.

CAREM-25 (in Spanish, 'Central Argentina de Elementos Modulares') is an Argentine nuclear reactor based on an indirect cycle with some distinctive and characteristic features that greatly simplify its design. These include an integrated primary cooling system, a self-pressurized primary system and safety systems relying on passive features. The first step of this project is the construction of a 27 MW(e) (CAREM-25) prototype at the Atucha nuclear site.

The Canadian enhanced CANDU 6 (**EC6**) is a 740 MW(e) pressure tube reactor designed by Candu Energy. The EC6 design incorporates the principles and characteristics of the CANDU 6 design, such as natural uranium fuel; two independent safety shutdown systems; a separate low-temperature, low-pressure moderator (that provides an inherently passive heat sink by permitting heat to be removed from the reactor core under abnormal conditions); a reactor vault filled with cool light water that surrounds the reactor core and provides a further passive heat sink; on-power refuelling; and a modular, horizontal fuel channel. The EC6 design includes a more robust containment (e.g. thicker walls, steel liner), enhanced severe accident management, the addition of an emergency heat removal system as a safety system, wider LOCA margins and a plant life of 60 years with one life extension of critical equipment such as fuel channels and feeders at midlife. The Canadian Nuclear Safety Commission (CNSC) is currently conducting the design review of the EC6.

The European pressurized water reactor (**EPR**) is the result of a joint development effort by Framatome and Siemens, and is now being made available by AREVA. It is a 1600+ MW(e) four-loop PWR design. In the EPR, the designers have chosen to use active safety systems and to increase redundancy in power sources and water inventories to smooth any potential transients. The EPR also has a double concrete containment and a core catcher for the mitigation of severe accidents. Its core is designed to operate with both UO_2 and MOX fuel, and reduced uranium consumption is expected. The EPR has been designed to operate under load following conditions, at between 20% and 100% of rated generator power. It includes fully digital I&C systems. EPR reactors are currently under construction in China, Finland and France.

GE Hitachi Nuclear Energy's economic simplified boiling water reactor (**ESBWR**) is a 1500 MW(e) reactor design based on the earlier 670 MW(e) simplified boiling water reactor (SBWR) design. Like the earlier SBWR design, the ESBWR design incorporates innovative features designed to further simplify an inherently simple direct cycle reactor. The ESBWR completely relies on passive safety systems for both normal and off-normal operating conditions, such as natural circulation, isolation condensers or gravity driven cooling systems. The core of the ESBWR is shorter and the overall vessel height is larger than in a conventional BWR, in an effort to maximize natural circulation and avoid the use of recirculation pumps or their associated piping. The USNRC issued an advanced safety evaluation report with no open items for the ESBWR in August 2010, and final design certification is expected shortly.

The integrated modular water reactor (**IMR**) developed by MHI is a medium sized power reactor with a reference output of 350 MW(e) and an integral primary system reactor with potential deployment after 2020. It employs a hybrid heat transport system, which is a natural circulation system under bubbly flow conditions for primary heat transportation, and no penetrations in the primary cooling system thanks to an in-vessel control rod drive mechanism. These design features enable the elimination of the emergency core cooling system. Because of its modular characteristics, the IMR is not only suitable for large NPPs consisting of several modules but also for small plants, especially when the capacity of the grid is small. The IMR is also capable of providing district heating, seawater desalination and process steam production.

India has developed its own pressurized heavy water reactor (**IPHWR**) design that consists of 220 MW(e), 540 MW(e) and 700 MW(e) units. India currently operates fifteen 220 MW(e) units and two 540 MW(e) units. Construction of three 700 MW(e) units is under way. The IPHWR was developed on the basis of experience gained in operating earlier units and from national R&D efforts. The important features introduced in these units include two diverse and fast acting shutdown systems, double containment of the reactor building, a water filled calandria vault, an integral calandria end shield assembly, and a calandria tube filled and purged with carbon dioxide to monitor pressure tube leaks by monitoring the dew point of carbon dioxide. These units also include a valveless primary heat transport system and a unitary control room concept, as well as advanced I&C systems.

The **international reactor innovative and secure, IRIS**, is a modular light water reactor with an integral primary system configuration designed by an international group comprising 20 organizations from nine countries. It features a simplified compact design in which the primary vessel houses steam generators, pressurizer and pumps, a novel safety approach, and an optimized refuelling cycle with intervals of at least four years. Due to the integral configuration of the IRIS, a variety of accidents are by design either eliminated or their consequences and/or probability of occurring can be greatly reduced.

The **KERENA** is an evolutionary boiling water reactor based on the experience gained from the proven engineering of current generation BWR plants supplemented by an innovative approach. The current final basic design of KERENA is part of a strategic partnership between AREVA NP and the German utility E.ON Kernkraft. In KERENA, safety systems have been simplified by introducing passive safety systems and most nuclear safety functions are performed by active systems with a passive system as a backup. The core height has been reduced to promote natural circulation, and the eight reactor water recirculation pumps are so-called 'wet-motor pumps', in which the electric pump motor is situated inside the reactor coolant pressure boundary.

The **KLT-40S** is a PWR based on the commercial KLT-40 marine propulsion plant and it is an advanced variant of the reactor plants that power nuclear icebreakers. The construction of a small floating nuclear cogeneration plant with two KLT-40S reactors is currently under way in the Russian Federation. The KLT-40S is a modular design in which the reactor, the steam generators and the main circulation pumps are connected by short nozzles (without long pipelines). It is a four-loop system which features forced and natural circulation of the primary coolant, with a once-through coiled steam generator, an external gas pressurizer system and passive safety systems.

A **NuScale** plant consists of 1 to 12 independent modules, each capable of producing a net electrical output of 45 MW(e). Each module includes a pressurized light water reactor operated under natural circulation primary flow conditions. Each reactor is housed within its own high pressure containment vessel which is submerged underwater in a stainless steel lined concrete pool. In early 2008, NuScale Power notified the USNRC of its intention to begin pre-application discussions aimed at submitting an application for the design certification of a twelve-module NuScale power plant. The reactor is now at the pre-application stage of design certification in the USA.

The **mPower** is a scalable and modular system in which the core and steam generators are contained within a single vessel. It is a modular reactor designed to match customer demand in 180 MW(e) increments. Its features include an integral nuclear system design, passive safety systems, a 4.5-year operating cycle between refuellings, 5% enriched fuel, secure underground containment, and a spent fuel pool with capacity to last for the lifetime of the plant. A scaled prototype of mPower using electric heating instead of nuclear heating is currently under construction in the USA to verify the reactor's design and safety performance. The reactor is now at the pre-application stage of design certification in the US.

The prototype fast breeder reactor **(PFBR)** is a 500 MW(e), sodium cooled, pool type reactor with two primary and two secondary loops featuring four steam generators per loop. The reactor is under construction at Kalpakkam, India. The primary objective of the PFBR is to demonstrate the techno-economic viability of fast breeder reactors on an industrial scale. The reactor's power output level was chosen so as to enable the adoption of a standard turbine as used in fossil power stations, to have a standardized design in reactor components resulting in further reduction of capital cost and construction time and to ensure compatibility with regional electricity grids. The reactor assembly houses the cold and hot pool components apart from the main vessel, the safety vessel and the top shield. The main cold pool components are the core catcher, the core support structure and the grid plate. The main hot pool components are the control plug and its internals, the inner vessel and the intermediate heat exchangers.

SMART, developed by the Korea Atomic Energy Research Institute (KAERI), is a 330 MW(th)/100 MW(e) integral PWR with inherent safety features including an integral configuration of the reactor coolant system, an improved natural circulation capability, a passive residual heat removal system and an advanced LOCA mitigation system. SMART has a low power density core that results in a thermal margin of more than 15% to accommodate any design basis transients with regard to the critical heat flux. SMART has been conceived as a multipurpose energy source that can also be used for non-electric applications such as seawater desalination, district heating or other industrial applications.

The **WWER-1000** is a Russian pressurized WCR that incorporates active and passive safety systems and has been adapted to Western standards based on the substantial design and operating experience accumulated in the Russian Federation over the last 50 years. It is currently under construction in India and the Islamic Republic of Iran. The **WWER-1200** is a scaled up version of the WWER-1000. Like its predecessor, it is a four-loop design with horizontal steam generators which have a track record of providing the longest operating life. The WWER-1200 also includes active and passive safety systems, double containment and severe accident mitigation systems, such as a core catcher.

The SVBR-100 is a Russian innovative small modular fast reactor with lead–bismuth eutectic alloy (LBC) as the coolant and a power output of

100 MW(e). The Russian Federation has planned to construct several SVBR-100 units. In the country, lead–bismuth cooled reactor technology has been used in eight different nuclear submarines. The experience gained from these reactors included: ensuring the corrosion resistance of structural materials, controlling the LBC quality and the mass transfer processes in the reactor circuit, and multiple LBC freezing and unfreezing in the reactor facility. The small reactor is in detailed design and will have a fuel cycle of 7–8 years with 16.3% enrichment. The SVBR-100 has a 60-year design life.

The Japanese **4S** reactor (super-safe, small and simple) is a small sodium cooled reactor without on-site refuelling in which the core has a lifetime of approximately 30 years. The 4S offers two outputs of 30 MW(th) and 135 MW(th), respectively selected on the basis of an analysis of energy demand. Although it has a fast neutron spectrum, the 4S is not a breeder reactor since blanket fuel (usually consisting of depleted uranium located around the core to absorb leakage neutrons from the core to achieve breeding of fissile materials) is not part of its basic design. The reactor power can be controlled by the water/steam system without affecting the operation of the core directly. The capacity for power self-adjustment makes the reactor suitable for a load following operation mode. The reactor is of the pool type and it is also an integral design since all the primary components are installed inside the reactor vessel.

IV–5. Conclusion

As seen in the previous sections of this document, various technology options for near- and mid-term use are available to countries considering starting a new nuclear power programme and every nuclear reactor design has its own key characteristics and benefits. The selection of the most suitable design requires an objective assessment of both the technical and economic benefits of each design, as well as of the associated technologies and related fuel cycle, all of which must be evaluated against the conditions and the needs of each country. Agency support is available to guide Member States in the process of evaluating these different technology options. Moreover, the Agency has developed a range of tools, such as the ARIS database, to provide Member States with balanced, comprehensive and up to date information regarding advanced reactor designs and concepts and to facilitate informed decision making.

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Annex V

THE ROLE OF RESEARCH REACTORS IN INTRODUCING NUCLEAR POWER

V–1. Introduction

Throughout the second half of the twentieth century, many countries saw research reactors as an essential step towards building their first nuclear power plants (NPPs). Times have changed; industrial experience and globalization now significantly facilitate the exchange of information and collaborative resource development. Nonetheless, in certain situations and provided that additional applications of the research reactor are well planned, a research reactor can still be a useful step towards nuclear power. This annex describes situations where a research reactor programme might contribute to the introduction of nuclear power, and how its utilization can be well planned.

Research reactors fulfil diverse needs, including medical and industrial isotope production, elemental analysis, silicon doping, neutron beam based science and applications, education and training, scientific research, and technology development (this includes support for existing and advanced nuclear power technologies). While a research reactor is not a prerequisite for nuclear power, the infrastructure developed to support the construction, regulatory approval, operation, maintenance and eventual decommissioning of a research reactor can help a country to introduce nuclear power. The infrastructure necessary for a research reactor is similar to that required for an NPP but often differs in scale. In addition, certain research reactor capabilities directly or indirectly support the development and implementation of nuclear power. Experience from managing nuclear material at research reactors promotes a better understanding of the infrastructure and issues that need to be addressed in the field of nuclear power.

Because the countries that now have nuclear power had access to operating research reactors before commissioning their first NPPs, several countries currently seeking to embark on nuclear power programmes for the first time are also considering either building their own research reactors or joining an existing research reactor coalition as a stepping stone towards nuclear power. In Morocco,

[1] The same is true in the case of building a first nuclear reactor for seawater desalination, heat energy production or other non-power purpose. The observations in this annex also apply to those applications.

for example, staff with experience from a project to build a new research reactor are now directly involved in their country's nuclear power planning. In contrast, the United Arab Emirates has taken a different approach and has contracted for its first NPPs without having previously operated a research reactor.

Countries considering the introduction of nuclear power may find that the experience gained from running a research reactor and managing nuclear material helps to facilitate studies that will allow them to make a knowledgeable decision about the long-term commitments required for nuclear power. The Agency's 'Milestones approach'[2] identifies 19 distinct national infrastructure issues to be addressed by countries considering the introduction of nuclear power programmes (Ref. V–1). Having a research reactor or other facility with nuclear material may mean that a country has already made progress on some of these issues, for example safeguards accountancy, nuclear security and regulatory oversight.

In particular, an existing research reactor programme and supporting infrastructure, when managed in accordance with international standards and accepted practices, can help in developing the infrastructure, experience and expertise of interest to a country's nuclear energy programme implementing organization (NEPIO). Treaties, legal frameworks, emergency response preparedness, and waste management policies and plans are examples of research reactor programme infrastructure of potential interest to a NEPIO. Similarly, experience derived from operating and regulating a research reactor, managing its fuel cycle, training its staff, assuring safety, continuously improving programmes, and managing a large capital project provides the NEPIO with an important reserve of domestic knowledge to draw on. The pool of experienced staff within the research reactor operating organization, regulatory authority and associated government agencies is a source of beneficial domestic expertise as a country begins to form a NEPIO. In Slovenia, for example, practically all nuclear professionals in the country began their career or attended practical training courses at the research reactor at Podgorica, Montenegro. In Malaysia, technical staff from an electric utility are being trained by research reactor operators in preparation for introducing nuclear power.

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[2] The publication *Milestones in the Development of a National Infrastructure for Nuclear Power* (IAEA Nuclear Energy Series No. NG-G-3.1, Vienna (2007) identifies three phases of infrastructure development, each with its own 'milestone'. Milestone 1 represents sufficient analysis of those 19 issues to enable a country to consider itself ready to make a knowledgeable commitment to a nuclear energy programme. Milestone 2 represents the necessary accomplishments in the areas to which each issue relates prior to inviting bids for an NPP. Milestone 3 represents the necessary accomplishments in all of these areas to be ready to commission and operate a first NPP.

Conversely, countries with underutilized or shut down research reactors that are not managed in accordance with international standards and accepted practices may have legacy issues to overcome before they can introduce nuclear power. Dysfunctional infrastructure, institutional inertia and laws, practices, policies and protocols unsuitable for commercial nuclear power may have to be revised to match the needs of a nuclear power programme. In this case, a prior research reactor programme might turn out to be a burden for the NEPIO, albeit one that must be addressed in any case.

The NEPIO will complete comprehensive reviews of all the issues to be covered before each milestone can be attained. The infrastructure, experience and expertise gained from one or more research reactors that have been safely and reliably operated, heavily utilized and well maintained could help in attaining milestones for several of the 19 issues specified by the Agency.

V–2. Selected Issues for Which Research Reactor Programmes can Pave the Way for Nuclear Power

V–2.1. National position

The foundations of a country's national position on nuclear power are significantly different to those on which a national research reactor programme might rest. Government support may (and does) exist for research reactor programmes in countries politically opposed to nuclear power. For example, in Australia a new research reactor called the Open Pool Australian Light Water (OPAL) Reactor started operation in 2007, even though national policy there excludes nuclear power. Similarly in Germany, which established a nuclear power phase-out policy in 2000, the FRM-II research reactor at the Technical University in Munich was subsequently commissioned in 2005.

However, despite the apparent lack of linkage, many key infrastructure requirements related to Milestone 1 for a country's national position on nuclear power will have typically already been considered within the scope of a research reactor programme. This experience could help develop an understanding within a NEPIO, energy ministry or a public utility of:

- The need to ensure the safety, security and non-proliferation of nuclear material;
- The need to adhere to appropriate international legal instruments;
- The need to develop a comprehensive legal framework covering all aspects of nuclear law, which includes safety, security, safeguards and nuclear liability and other legislative, regulatory and commercial aspects;
- The need to have an effective, independent, competent regulatory body;

- The need to develop and maintain national human resource capabilities within both government and industry to successfully manage, operate, maintain and regulate nuclear facilities and nuclear material as well as preserve knowledge and expertise.

Similarly, in implementing the actions recommended for Milestone 2 for a country's national position on nuclear power, governments will benefit from the experience of a research reactor programme, but any measures adopted as part of the latter will likely have to be revised to support nuclear power. Examples include:

- The expansion of an existing regulatory body;
- The establishment and maintenance of an effective State system of accounting for and control of nuclear material to facilitate the implementation of the State's safeguards commitments;
- An established policy for the nuclear fuel cycle, including arrangements for secure supplies of fuel, safe and secure transportation and storage of new and spent fuel, and long term waste management;
- Established legal, organizational and financial arrangements for decommissioning and radioactive waste management;
- Programmes for the security of nuclear materials and facilities;
- Programmes for radiation protection and emergency preparedness and response;
- Adopted international standards for environmental protection.

V–2.2. Nuclear Safety

The operator's prime responsibility for safety is as important for a research reactor as it is for an NPP, as is the need for the government and all other stakeholders to appreciate what this means in practice. In particular, similarly stringent safety requirements must be implemented by both research reactor staff and nuclear power staff. The need for an effective regulatory body is just as important in both cases and is considered in a later section of this annex.

In most cases, countries with heavily utilized, well maintained and reliable research reactors will be able to easily demonstrate that programmes are implemented consistently with fundamental safety principles and other internationally recognized safety standards. Nuclear power newcomer countries with established research reactor programmes that are operated and maintained in accordance with such standards will generally already be participating in the global nuclear safety regime.

With respect to Milestone 1 for nuclear safety, relevant aspects of a research reactor programme may help a NEPIO achieve specific objectives. Examples include domestic expertise and experience in fostering and maintaining a nuclear safety culture, stakeholder involvement and participation in the global nuclear safety regime. The NEPIO will have to ensure that the safety culture is adequate for introducing nuclear power and take any necessary actions to instil a safety culture in stakeholders not normally involved with research reactors, e.g. utilities, industrial organizations and energy related government agencies (as opposed to those agencies involved in science and research).

With respect to Milestone 2, the requirements relate more specifically to nuclear power and the need to ensure that the relevant stakeholders adopt the proper practices and culture. However, expertise and experience from government organizations responsible for research reactors, from the research reactor regulator and from operating organizations could be used by the NEPIO to help ensure that all nuclear safety related objectives are satisfied.

V–2.3. Legislative framework

Countries with an active research reactor programme are likely to have an existing legislative framework that may provide an adequate basis for the legislative framework needed to support nuclear power. Many international legal instruments that are necessary for nuclear power are also necessary for a research reactor programme. In any case, national legislation should comprehensively cover nuclear safety, security, safeguards and liability for nuclear damage.

A number of elements related to Milestone 1 will typically already exist for a research rector programme, but must still be reviewed by the NEPIO for possible revision to support nuclear power. Examples include:

- Established and effectively independent regulatory authorities and legislation dealing with
  - a system of licensing, inspection and enforcement,
  - radioactive material and radiation sources,
  - the safety of nuclear installations,
  - emergency preparedness and response,
  - nuclear related transport of nuclear material,
  - radioactive waste and spent fuel,
  - nuclear liability and coverage,
  - safeguards,
  - export and import controls, and
  - physical protection;

— Legislation dealing with the roles of the national government, local government authorities, the public and other stakeholders;
— Legislation dealing with fuel cycle issues in general and the ownership of nuclear material;
— Provision for the development of human resources to ensure the continued integrity of the nuclear programme;
— The commitment to use nuclear technology and techniques for peaceful purposes.

Likewise, for Milestone 2, elements of the required legislation for nuclear power will have been developed to support research reactors but will likely have to be revised. Examples include:

— Appropriate national legislation pursuant to the relevant non-proliferation undertakings of the State;
— Legislation that specifies the allowed ownership of nuclear facilities and nuclear materials; the legislation establishes clear responsibilities and liabilities for the operation of nuclear facilities and safeguarding of nuclear material;
— Legislation that establishes an effectively independent regulatory body with full authority to implement the functions assigned to it by the enabling legislation.

V–2.4. Regulatory framework

A country embarking on a nuclear power programme will consider how to efficiently build on the national infrastructure already in place for radiation, waste and transport safety. Expanding the existing regulatory body for a research reactor so that it can also act as the regulator for an NPP may be the best way to utilize existing facilities and human resources that are likely to be limited in many countries.

With respect to Milestone 1, many fundamental elements of a regulatory framework will be in place to support an existing research reactor programme but must still be reviewed by the NEPIO for possible revision to support nuclear power. Examples include:

— Designation of an effectively independent regulatory body, with clear authority and adequate human and financial resources;
— Regulations for licensing, review and assessment, inspection, enforcement and public information;

— Authority to obtain technical support as needed;
— Authority to implement international obligations, including IAEA safeguards;
— Provisions for stakeholder and public information and interactions;
— Compatibility with the existing regulatory framework for radiation, waste and transport safety.

Similarly for Milestone 2, a number of important issues would be familiar to a regulatory body established for research reactors, but will also likely have to be revisited for nuclear power. Examples include:

— Safeguards;
— Nuclear and radioactive materials transportation, handling and storage;
— Radiation protection;
— Waste management, including disposal;
— Codes and standards developed or adopted for:
  • The import/export, transportation, storage and handling of nuclear and other radioactive material;
  • Radiation protection;
  • Waste management;
  • Emergency preparedness and response.

V–2.5. Security and physical protection

Nuclear security requires the concerted effort and commitment of all organizations involved in the planning, design, construction and operation of a nuclear research or power reactor. It is critical that these organizations acknowledge the importance of nuclear security and embrace a nuclear security culture. With respect to Milestone 1, an existing research reactor programme should demonstrate a country's commitment to a strong nuclear security culture. The NEPIO will work to ensure that the existing security culture is adequate for the introduction of nuclear power and take any necessary actions to instil a security culture in stakeholders not normally involved with research reactors, e.g. utilities, industrial organizations and energy related government agencies (as opposed to those agencies involved in science and research).

With regard to Milestone 2, several conditions should already exist in countries with a well managed research reactor programme. As is the case above, existing programmes will likely have to be revised to support nuclear power. Examples include:

- Legislation providing appropriate authorities for security and physical protection;
- Protocols and programmes for local and national law enforcement;
- Programmes for the definition of sensitive information, protection requirements and associated penalties;
- Laws providing for penalties for malicious acts, illegal possession and trafficking of materials, as described in international legal instruments;
- Programmes for the careful selection and qualification of nuclear programme staff with access to facilities or sensitive information.

V–3. Utilization Planning

Careful consideration is essential before committing to start a new research reactor programme to avoid unnecessary burdens, underutilization and the significant legacy issues currently faced by many research reactors worldwide. While a new research reactor programme can, over time, serve to facilitate the introduction of nuclear power just like an existing research reactor programme, experience suggests that the support provided by a new or existing nuclear power programme is inadequate on its own to sustain long-term research reactor operation. Most nuclear utilities develop customized training programmes, and nuclear engineers make up only a minor proportion of the workforce at an NPP (Ref. V–2).

The decision to embark on a research reactor programme and the decision to introduce nuclear power are similar in that both involve long-term commitments related to facility construction, operation, decommissioning and the ultimate disposition of all waste. A major important difference between the two, however, is the funding of operation, maintenance, waste management and decommissioning. Nuclear power plant financing and funding requirements are typically at least an order of magnitude greater than those of a research reactor. Even more important is the fact that NPPs generate revenues to cover these costs, while most research reactors are funded and operated with government funds. Most are not financially self-sustaining and require continuing government financial support throughout the entire period of operation and decommissioning.

The utilization plan for an NPP is straightforward. It should operate as consistently as possible with safe and secure programmes and procedures. For research reactors, utilization planning is less straightforward. A robust utilization plan is needed from the very beginning of the planning. Underutilized research reactors may struggle to justify and secure adequate funding to be properly maintained. This makes it harder to ensure adequate safety, security and environmental stewardship. A robust utilization programme and strategic plan can help to ensure sustainable funding to fulfil a country’s or region’s long-term needs in terms of research, education and training, isotope production and other related aspects. A research reactor constructed without a thorough utilization analysis could be faced with reduced utilization and funding cuts.

A research reactor constructed mainly or solely to support the introduction of nuclear power may lose its principal value after the first NPPs are commissioned because a nuclear power programme can be sustained without national research reactors. For example, nuclear power continues in Spain and Sweden although all their research reactors have been shut down. Also, following the breakup of the former Soviet Union and the division of Czechoslovakia, Armenia, Slovakia and (until 2009) Lithuania have maintained nuclear power without domestic research reactors.

On the other hand, some countries with nuclear power are reconsidering the role of their research reactors. For example, plans to shut down a research reactor at Imperial College, London, have been reversed at least in part to support human resource development for an expected expansion of nuclear power. Also, construction of a new training reactor is being considered in Sweden.

Figure V–1 illustrates that practical or vocational training is an important component of nuclear education and infrastructure development for nuclear power. In addition, formal training and education programmes must be established for people throughout the full range of a country's nuclear power infrastructure, i.e. students, engineers, operators, inspectors, regulators, managers and even the general public. Access to research reactors — particularly those designed to support training programmes — can help satisfy both formal and vocational education needs. Such access could be through a domestic research reactor or partnership in a research reactor coalition.

An example of a country using domestic research reactors in support of nuclear power is France. France uses a range of training methods that includes software applications, training research reactors and dedicated simulators. The combination of these different tools provides a comprehensive understanding of reactor design, physics phenomena, operation and safety principles. In this context, the ISIS research reactor of the French Alternative Energies and Atomic Energy Commission (CEA)'s National Institute for Nuclear Sciences and Technology (INSTN) in Saclay has been refurbished and adapted to be used for nuclear training. It now provides more than 100 hands-on training courses annually for nuclear and non-nuclear engineering students, reactor operators, safety authorities and nuclear industry specialists both from France and other countries. The Czech Republic uses a similar approach. Figure V–2 illustrates training courses at the VR-1 training research reactor of the Czech Technical University (CTU) in Prague.

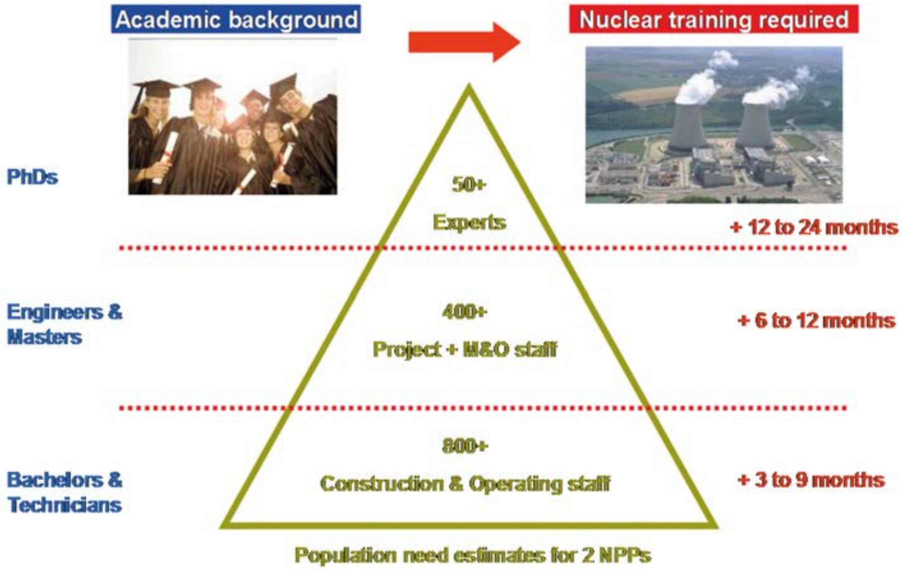

FIG. V–1. The need for basic academic qualifications (on the left) and supplemental specialized nuclear training (on the right) for staff at all required levels for building, operating and managing a first NPP with two reactor units. (M&O = operation and maintenance) Source: AREVA, France.

Research reactor coalitions help countries that would like to support their nuclear power programmes with training at research reactors but are unable to justify operating domestic research reactors. Coalitions allow access to existing research reactors in other countries to help develop the necessary human resources and skills with little delay (see Ref. V–2). Such shared access can allow countries without research reactors of their own to take advantage of other countries' established infrastructure, including their competence in nuclear technology and their mature safety and security cultures.

Research reactors are well suited to this role. Many have utilization programmes specifically developed for nuclear related training and education and are often very willing to accommodate the needs of other countries. Austria, for example, has no nuclear power programme, but the research reactor in Vienna is a founding member of the East European Research Reactor Initiative (EERRI) and supports the nuclear education and training programmes of other countries. These include training NPP operators from other countries. Another example is in Jordan, where the Jordan University of Science and Technology is using a web-based video system to permit its nuclear engineering students to complete exercises and experiments as if they were present in the control room of a research reactor at the North Carolina State University in the USA.

FIG. V–2. Training courses at the VR-1 training research reactor of the Czech Technical University (CTU) in Prague.

Other examples include:

- The TRIGA Mark II reactor located at the University of Mainz, Germany. Here, a broad range of courses are offered related to nuclear engineering, including reactor operation and reactor physics, nuclear chemistry and radiation protection.
- The AGN-201K reactor at the Kyung Hee University, Republic of Korea. Between January 2009 and December 2010, 12 courses were completed at this reactor for 128 nuclear engineering students from 7 universities.
- The IPR-R1, TRIGA Mark I reactor at the Nuclear Technology Development Centre in Belo Horizonte, Brazil. Most of Brazil's NPP operators and other technical staff have been trained at the IPR-R1 reactor. As of December 2010, more than 250 nuclear energy workers were certified by an operator training course on research reactors. This course was designed as part of the first phase of the power reactor operator training programme.

Additional data for selected research reactor training programmes that support existing nuclear power programmes are provided in Table V–1.

TABLE V–1. ROLE OF RESEARCH REACTORS IN EDUCATION AND TRAINING FOR NUCLEAR POWER UTILITIES, SUPPORT INDUSTRY AND SAFETY AUTHORITIES

Country – Research Reactor	Number of staff trained			
	2008	2009	2010	2011
Austria*, TRIGA Mark II, 250 kW	15	15	15	8
Brazil, IPEN/MB-01, 0.1 kW	0	23	0	37
Czech Republic**, VR-1, 5 kW	13	31	51	33
France, ISIS reactor***, pool, 700 kW	290 (i=11%)	310 (i=17%)	350 (i=32%)	400 (i=30%)
France, MINERVE, critical facility	40	40	40	60
Germany****, AKR-2	41	50	44	25
Italy, TRIGA Mark II, 250 kW	0	47	47	24
Malaysia, TRIGA Mark II, 1000 kW	20+	—	10++	—
Slovenia, TRIGA Mark II, 250 kW	51	41	32	70

* *For utilities in Slovakia*
** *For utilities in the Czech Republic and Slovakia*
*** Depending on the specific objectives, training course durations range from 3 to 24 hours (i = percentage of international students)
**** *For 9 other countries*
+ 17 engineers from a utility, 3 lecturers from a university
++ All lecturers from a university

V–4. Conclusion

The support infrastructure, experience and expertise fostered by an existing, well utilized and effectively managed research reactor programme can contribute to the understanding which a country needs in order to make knowledgeable decisions regarding nuclear power. In particular, a competently managed research reactor programme will be backed up by national laws, international legal instruments and organizational infrastructure with features similar to those required for sustaining nuclear power. Research reactors can foster domestic safety and security cultures that are difficult to achieve in the absence of active programmes and the day to day hands-on experience that these entail. In addition, research reactors can support an existing or beginning nuclear power programme, particularly with regard to training, research and technical support.

On the other hand, a poorly managed research reactor programme can add a significant burden to the efforts of a NEPIO. In some cases, existing infrastructure will have to be significantly revised to address the needs of a nuclear power programme. Thorough assessments by the NEPIO and other national oversight organizations will determine the best path forward.

Countries have benefited in the past from starting research reactors before launching nuclear power programmes. Today they can benefit from the research reactor capabilities offered through partnerships with others, through either a regional research reactor facility or a coalition. In these cases, the capabilities of the existing reactor, the approach to nuclear safety and security, and the value and relevance of its training programmes can be assessed in advance.

For those countries which choose to construct a new research reactor as a stepping stone towards nuclear power, identifying other uses for the facility will help to ensure its long-term viability. A robust utilization plan, developed with input from a broad community of potential users and customers, will be reflected in high levels of utilization, the availability of necessary funding, and long-term safe, sustainable and environmentally responsible operation of the facility.

REFERENCES

[V–1] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G-3.1, IAEA, Vienna (2007).

[V–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Human Resources for Nuclear Power Expansion (Supplement to Nuclear Technology Review 2010 (IAEA document GC(54)/INF/3 issued on 10 August (2010)).

Annex VI

THE USE AND MANAGEMENT OF SEALED RADIOACTIVE SOURCES

A sealed radioactive source (SRS) is defined as “radioactive material that is either permanently sealed in a capsule or closely bonded and in a solid form”.[1] The capsule or material of a sealed source is strong enough to maintain leak tightness under the conditions of use for which the source was designed and also under foreseeable mishaps. This document summarizes the uses as well as the safe and effective management and disposal of SRSs.

VI–1. Introduction

Sealed radioactive sources are widely used for beneficial purposes throughout the world in industry and in medicine. In industry, common uses include non-destructive testing, radiation sterilization of health care products, modification of polymeric materials, on-line process control systems, elemental analysis of raw materials, mineral resource evaluation, food irradiation and smoke detection. In medicine, SRSs are commonly used in teletherapy and brachytherapy for the treatment of malignant diseases and for blood irradiation. Some well known examples of such sources are: cobalt-60 sources for teletherapy, brachytherapy, food irradiation, sterilizing health care products, and measuring thicknesses, densities and other important properties in industrial processes; iridium-192 sources for industrial radiography and brachytherapy; americium-241 sources for smoke detectors; and caesium-137 sources for brachytherapy and blood irradiation.

The activity of these sources ranges from tens of kilobecquerels (kBq) (1 Bq = 2.7×10^{-11} curies (Ci)) in sources used for calibration purposes to hundreds of terabecquerels (TBq) in industrial irradiators and sources used in radiation therapy. The radioactive isotopes employed in SRSs are used in a variety of chemical and physical forms: metallic or oxide, impregnated into ceramics or electroplated onto other support metals as thin films or deposits. The radioactive isotopes are then encapsulated in inert metallic capsules to produce the SRSs proper. These are finally enclosed in various devices that can channel a direct radiation beam at the target material or target tissues while shielding operational personnel from unwanted exposure.

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[1] It should be noted that the therapeutic treatment of certain tumours is also practised at some facilities using fast neutron beams.

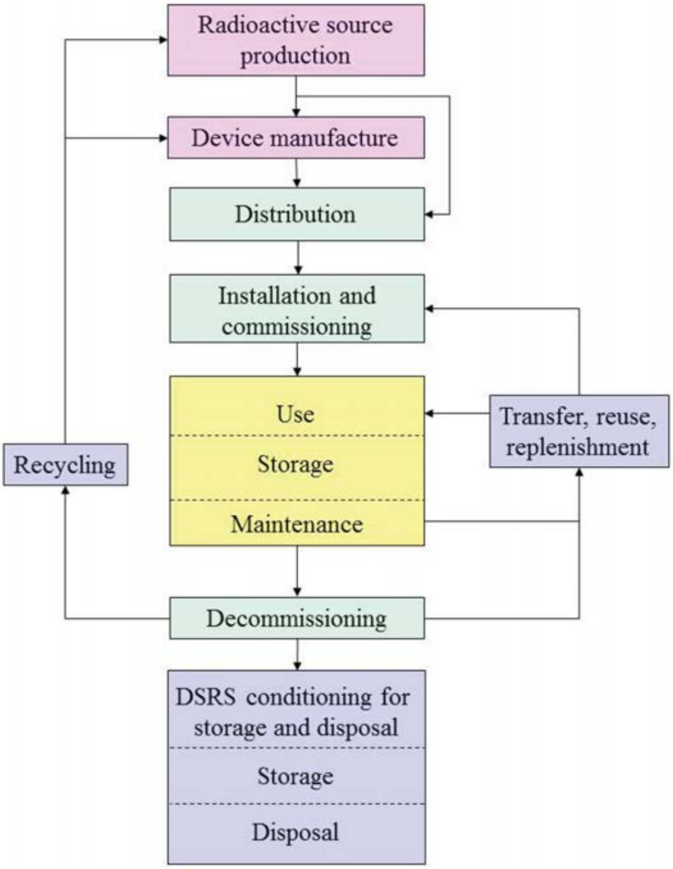

FIG. VI–1. Life cycle of sealed radioactive sources.

The life cycle of sealed radioactive sources, from the radioactive source production to its eventual disposal is represented in Fig. VI–1. Once sealed sources become disused (e.g. once they cannot accomplish their intended purpose anymore due to radioactive decay), if they are not managed safely and securely, they may leak, become abandoned or be lost, stolen or misused by unauthorized persons, causing radiation incidents or accidents. The IAEA defines a 'disused source' as "a radioactive source that is no longer used, and is not intended to be used, for the practice for which an authorization has been granted"[2]. 'Spent sources' (a sub-set of disused sources) are those that are "no longer suitable for

[2] *IAEA Safety Glossary: 2007 Edition,* IAEA, Vienna (2007), *http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf.*

[their] intended purposes as a result of radioactive decay”[3]. The term ‘disused source’ (or DSRS, disused sealed radioactive source) is used as defined above throughout this document.

Some of the challenges involved in the industrial and medical use of high activity sources, mainly cobalt-60 sources, include the existence of a limited number of suppliers, security concerns and frequent transport delays. Furthermore, in light of the widespread use of radioactive sources around the world and their long half-lives, the safe management and disposal of DSRS needs to be ensured.

Partly as a result of these challenges, there has been a shift from the use of radioactive sources to electron accelerators in industrial applications, and to X rays in research and development (R&D) work in radiation chemistry and biology. This shift away from cobalt-60 based teletherapy can also be observed in radiation medicine and is a consequence of the proven superiority of linear accelerator (linac)-based radiation therapy. Nonetheless, cobalt-60 sources are still preferred for many applications, and there is a continuing need for new sources to either replace or to replenish disused sources in existing cobalt-60 based systems.

VI–2. Uses

VI–2.1. Industrial applications

VI–2.1.1. Radiation processing

Radiation sources are used in industrial applications to help modify the physical, chemical and biological properties of the irradiated materials, forming the basis of radiation processing. The principal applications of radiation processing today are: sterilizing health care products; irradiating food products (for disinfection, hygiene, sterilization, to kill pests, to extend shelf life or inhibit sprouting); disinfecting wastewater; modifying materials for polymer-based products such as cables, tubes, tapes, hydrogels and tyre belts; and colouring gemstones. Radiation processing adds value to products and its use is increasing with industrialization and economic development worldwide.

One of the major applications of radiation processing based on cobalt-60 sources remains the sterilization of health care products, established over five decades ago as an alternative to ethylene oxide and steam-based technology.

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[3] *IAEA Safety Glossary: 2007 Edition,* IAEA, Vienna (2007), *http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf.*

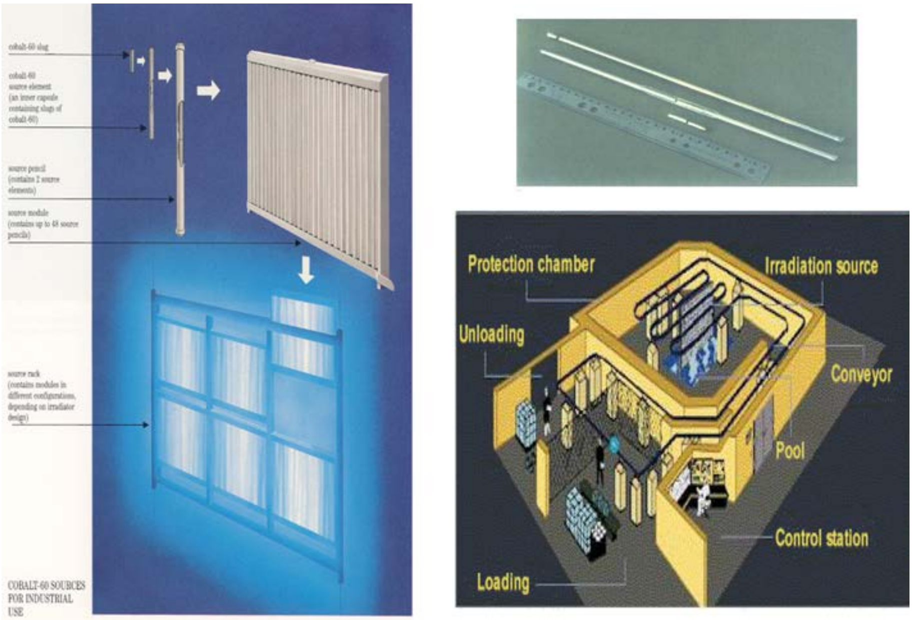

FIG. VI–2. Slugs (small cylinders) of cobalt-60 are arranged in source elements, source pencils and source modules to make up a typical cobalt source rack. The picture on the bottom right illustrates a typical cobalt-60 gamma radiation facility.

About 85% of the 200 or so commercial industrial gamma facilities currently operating worldwide are used to sterilize health care products, and even more are being planned and built. The IAEA's Database of Gamma and Electron Beam Irradiation Facilities[4] lists most of them.

Cobalt-60, with a half-life of 5.27 years, and caesium-137, with a half-life of 30.1 years, are the best gamma radiation sources because of the relatively high energy of their gamma rays and their fairly long half-lives. Caesium-137, however, is used only in small self-contained dry-storage irradiators, primarily to irradiate blood and sterilize insects. All other industrial radiation processing facilities use cobalt-60.

Figure VI–2 shows a typical cobalt-60 source rack. It is generally made up of modules, each containing up to 48 source pencils. Each source pencil has two source elements each, i.e. thin cylinders containing slugs of cobalt-60. With a half-life of 5.27 years, the strength of a cobalt-60 source decreases by about 12% per year. Additional pencils of cobalt-60 are added periodically to the source rack to maintain its required source strength. At the end of their useful life, typically

[4] See *http://www-nds.iaea.org/iacs_facilities/datasets/foreword_home.php*.

20 years, cobalt-60 pencils are removed and generally returned to the supplier for re-use, recycling or disposal. After about 50 years, 99.9% of the cobalt-60 contained in the pencils decays into non-radioactive nickel. Depending on its original value, the remaining 0.1% radioactivity may still pose a considerable radiological risk.

However, the acute supply shortage of cobalt-60 in recent years has been a major impediment to the construction of new cobalt-60 irradiation facilities. It is also an important concern for functioning irradiation units, as these will need the cobalt-60 isotope for replenishing the decayed activity from time to time. The re-use of cobalt-60 sources has found strong support not only thanks to this shortage but also to the current economy. Manufacturers and suppliers are increasingly exploring options to collect used cobalt-60 sources from medical facilities and appropriately modify them in order to re-qualify them for use in industrial facilities which need much less intense sources.

VI–2.1.2. Industrial process management

Sealed radioactive sources were first utilized in industry over forty years ago and are now widely used to control and troubleshoot industrial processes, as summarized in Table VI–1.

In smoke detectors, the first item in Table VI–1, the very small americium-241 alpha source ionizes air in a chamber in the absence of smoke. When smoke enters the chamber and reduces the air ionization, tripping the current, the alarm is triggered. Other items in the Table reflect the several hundred thousand nucleonic control systems and nucleonic gauges installed in industrial processes and plants around the world. Each nucleonic control system or nucleonic gauge incorporates one or more SRSs of alpha, beta, gamma, neutron or X ray radiation arranged in a fixed geometrical relationship with one or more radiation detectors.

Nucleonic control systems are used:

- In on-line industrial processes to measure densities, thicknesses, levels and concentrations and to carry out elemental analysis;
- In off-line processes to do bulk sampling of coal and other minerals;
- In in-situ well logging associated with mining coal and minerals;
- In laboratories to analyse e.g. the moisture of coal ash samples;
- In portable devices used in industrial facilities for on-site measurements of material thicknesses, blockages, corrosion, densities and moisture.

TABLE VI–1. SEALED RADIOACTIVE SOURCES IN INDUSTRIAL PROCESS MANAGEMENT

Radionuclide	Half-life	Typical radiations used (Energies in MeV)	Major applications	Physical or chemical form	Typical activity (TBq [Ci])
Americium-241	432.2 y	α (5.49, 5.44)	Smoke detector Radioisotope thermoelectric generator	Pressed powder (americium oxide)	0.5–0.8 [13–22]
Americium-241/ Beryllium	432.2 y	n ($4.4_{average}$)	Well logging in oil exploration Borehole logging and elemental analysis in mineral exploration Thickness gauging for light alloys, glass, plastics, and rubber	Mixture of americium oxide and beryllium metal	100–740 [3–20]
Californium-252	2.645 y	α (6.22)	Well logging in oil exploration Moisture gauge	Metal oxide	0.0004 [0.011]
Caesium-137 (Barium-137m)	30.17 y	γ (0.662)	Gamma irradiators Level gauge Calibrators/check sources	Pressed powder (caesium chloride)	75 [2000] 50 [1400] 15 [400] 0.00004 [0.001]
Cobalt-60	5.27 y	γ (1.17, 1.33)	Gamma irradiators Industrial gamma radiography	Metal slugs Metal pellets	150k [4 million] 500[14 000] 4 [100]
Iridium-192	74 d	γ ($0.380_{average}$)	Industrial gamma radiography	Metal pellets	4 [100]

TABLE VI–1. SEALED RADIOACTIVE SOURCES IN INDUSTRIAL PROCESS MANAGEMENT (cont.)

Radionuclide	Half-life	Typical radiations used (Energies in MeV)	Major applications	Physical or chemical form	Typical activity (TBq [Ci])
Plutonium-238	87.7 y	α (5.59)	Radioisotope thermoelectric generator Radioisotope heater unit	Metal oxide	10 [270] 8 [200]
Selenium-75	119.8 d	γ ($0.280_{average}$)	Industrial gamma radiography	Metal compound	3 [75]
Strontium-90 (Yttrium-90)	28.9 y	β (0.546)	Radioisotope thermoelectric generator	Metal oxide	750 [20 000]

FIG. VI–3. Thickness gauge used in paper production. Typical sources include: ^{90}*Sr (370 MBq (10 mCi) to 3.7 GBq (100 mCi));* ^{85}*Kr (370 MBq (10 mCi) to 18.5 GBq (500 mCi));* ^{147}*Pm (3.7 GBq (100 mCi) to 18.5 GBq (500 mCi)).*

Industrial sectors that make substantial use of nucleonic control systems and nucleonic gauges are oil and gas, mining and mineral ore processing, environmental monitoring, paper and plastics, cement and civil engineering. Figure VI–3 shows a nucleonic gauge used to measure the thickness of paper.

VI–2.1.3. Non-destructive testing using radioactive sources

Sealed radioactive sources are used in gamma radiography for non-destructive testing (NDT). Gamma radiography is similar to medical X ray radiography, where the attenuation of the X rays is used to obtain a picture of the internal structures of the human body. However, industrial radiography involves imaging the inner mechanisms of machines and structures which are much denser than the human body, and high energy radiation is necessary for the radiographic examination of these. In industrial radiography, therefore, instead of using an electrically powered high-voltage X ray generator to create the image, a radioactive source producing gamma rays is used. Gamma radiography provides a suitable alternative to X ray radiography, particularly in situations where there is no convenient power supply for an X ray generator or where work is conducted in confined spaces or in the field. Gamma radiography sources (mostly iridium-192, cobalt-60 and selenium-75 sources) are typically placed in a sealed protective metal casing in a transportable device, known as a projector or camera. The projector is positioned using a remote cable handling system and the gamma rays then pass through the specimen being radiographed onto a film to provide an image. The system is commonly used for NDT during construction projects such as buildings and pipelines, including the checking of structural welds.

The best SRSs for gamma radiography are small, have sufficient gamma ray energy to penetrate the thickness of the specimen being tested, have sufficiently long half-lives and high specific activity. They are used for radiography of welds, castings, forgings, plastics, composite materials, concrete etc. The industries in which their use is widespread include chemicals, petroleum, oil and gas, automobiles, aerospace, power generation (both nuclear and non-nuclear), civil engineering, welding, general engineering fabrication plants, and maintenance operations in many industrial processing plants.

VI–2.1.4. Materials analysis

When an element absorbs radiation of a known energy, it emits a unique spectrum of secondary X rays. This is called X ray fluorescence (XRF). Analysis of the spectrum allows an accurate determination of the composition of the material. The initial radiation can come from an SRS. However, it is important that the radiation from the source matches the absorption range of the element to be determined. As the atomic number of the element increases, the radiation from the source must also be more energetic. Hence, different isotopes are used to detect different elements. An SRS used for materials analysis is contained in a shielded device with a shutter that can be opened to allow collimated beams of radiation to be directed onto the material being analysed. The shutter is locked when the device is not in use. The detector is normally contained within the same unit as the source with associated electronics to analyse the spectrum of secondary X rays and identify the material.

Typical applications of such devices, which can be portable, include alloy analysis for checking stock, sorting scrap and checking components; the analysis of material excavated in mining operations from pits or from cores, as well as of chippings and slurries from drilling operations; the analysis of electroplating solutions; general laboratory chemical analysis; wood pulp and slurry analysis; agriculture; oil exploration and production; and the determination of lead levels in old paint to establish the level of personal protection required to remove it. The typical maximum activity levels used for different radioisotopes are 1.85 GBq (50 mCi) for americium-241; 3.7 GBq (100 mCi) for californium-244; 1.85 GBq (50 mCi) for cadmium-109; and 740 MBq (20 mCi) for iron-55.

VI–2.2. Medical applications

Sealed radioactive sources are also widely used to treat diseases. The most common uses are teletherapy, brachytherapy and blood irradiation.

FIG. VI–4. Cobalt-60 unit used for teletherapy (Typical source activity: up to 370 TBq (10 kCi) ^{60}Co).

In teletherapy, cobalt-60 is the most commonly used radioisotope-based radiation source in treating cancers. There are more than 2400 cobalt-60 teletherapy units around the world. Teletherapy is based on the fact that radiation kills fast growing cells, like cancer cells, more quickly than slower growing healthy cells. In teletherapy (Fig. VI–4), the dose of radiation is delivered to a well-defined area of the body that is affected by the disease.

The sources used in teletherapy need to be changed regularly. The preferred option is to return disused sources to their suppliers, but if this is not possible, the sources should be transferred to an authorized waste management organization for storage and disposal.

Another common medical use of SRSs is brachytherapy. In brachytherapy, the radioactive source is in direct contact with the patient, inserted into a tumour either directly by a surgical team or remotely using special equipment. The IAEA's Directory of Radiotherapy Centres[5] lists more than 200 high dose rate (HDR) cobalt-60 units, 900 HDR iridium-192 units and more than 1300 low dose rate (LDR) units worldwide.

There are two main types of brachytherapy treatment that use sealed sources: 'intracavitary', in which the sources are placed in body cavities close to the tumour, and 'interstitial', in which the sources are implanted within the tumour. Intracavitary treatments are always temporary and of short duration,

[5] See *http://www-naweb.iaea.org/nahu/dirac/default.asp*.

while interstitial treatments may be temporary or permanent. The advantage of brachytherapy treatments over external beam radiotherapy is the improved localized delivery of the dose to the target of interest. The disadvantage is that brachytherapy can only be used if the tumour is localized and relatively small. In a typical radiotherapy department, about 10–20% of all radiotherapy patients are treated with brachytherapy.

Brachytherapy uses both gamma sources and beta sources. The radioisotopes used for gamma sources are iodine-125, palladium-103, iridium-192, caesium-137, cobalt-60 and gold-198. Those used for beta sources are xenon-133, phosphorus-32, tungsten-188/rhenium-188, strontium-90/yttrium-90 and ruthenium-106/rhodium-106.

Brachytherapy gamma sources are available in various forms, including needles, tubes, seeds, wires and pellets. Usually they are doubly encapsulated both to provide adequate shielding against alpha and beta radiation, which is also emitted from the source, and to prevent leakage of the radioactive material.

Brachytherapy sources that are implanted permanently in a tumour never need to be replaced, but other sources used in brachytherapy do need to be replaced regularly. As with the sources used in teletherapy, the preferred option is to return the source to the supplier. If this is not possible, the sources should be transferred to an authorized waste management organization for storage and disposal.

A final medical use of SRSs is for blood irradiation to prevent complications associated with blood transfusions, such as transfusion-associated graft-versus-host disease (TA-GVHD). Dedicated blood irradiators (Fig. VI–5) contain gamma-emitting sources with long half-lives, e.g. caesium-137.

As discussed above, there are a wide variety of SRSs, varying in the type as well as the strength of the radioisotope used. Thus, SRSs may range from very small, low-activity, short-lived sources to very large and heavy long-lived sources that need to be highly shielded. This means that there will be disused sources of varied sizes, strengths and longevities which need to be disposed of in an appropriate manner. Therefore, managing disused SRSs is an issue of significant and continuing importance.

VI–3. Management of Disused Sealed Radioactive Sources

Most countries that have adequate regulatory infrastructures keep national or institutional records of SRSs in use, as well as of disused sealed radioactive sources (DSRS), and have adequate capabilities to ensure the safety and security of their sources. However, many countries are using SRSs in medicine, industry and agriculture without having effective regulatory systems and technical

FIG. VI–5. Blood irradiator unit (typical source activity: up to 250 TBq (7 kCi) ^{137}Cs; up to 25 TBq (7 kCi) ^{60}Co).

capabilities to manage the resulting DSRS. Consequently, there is no reliable information on the number of DSRS in these countries and a multi-year project has been proposed at the IAEA to develop a method to collect reliable data for a worldwide estimate.

V–3.1. Predisposal management of DSRS

Because poorly controlled DSRS have caused serious, even fatal radiation accidents, the IAEA has, almost since its inception, been involved in improving their control. Through its technical cooperation programme, the IAEA helps interested Member States to build up their regulatory and technical capabilities. It has helped nearly 50 countries to package and store old radium sources safely and securely and has successfully recovered thousands of sources. From 2007 to 2009, 5082 sources were recovered and safely stored in national storage facilities in the countries in which they were recovered and 202 sources were repatriated to their countries of origin. Thirty-eight of the sources were recovered using the mobile hot cell (MHC), a technology that was conceived by the IAEA and developed by the Nuclear Energy Corporation of South Africa (Necsa), under contract to the IAEA (see Fig. VI–6). The MHC is used to remove high activity DSRS from devices in the field. It is designed for gamma-emitting sources up to the equivalent of 37 TBq (1000 Ci) of cobalt-60, but has also met all necessary requirements during a test with a cobalt source of over 74 TBq (2000 Ci).

FIG. VI–6. The mobile hot cell in operation in Uruguay.

The MHC was introduced in 2009 and has been used in Sudan, the United Republic of Tanzania and, in 2010, in Uruguay. In Sudan and the United Republic of Tanzania, the sources that were extracted, characterized and safely packaged using the MHC were then safely stored in national facilities in those countries. In Uruguay, the sources were packaged into transport containers for repatriation to their countries of origin.

Most countries with advanced nuclear programmes and operating radioactive waste storage and/or disposal facilities have implemented disused source recovery programmes.[6] Countries without disposal facilities would prefer to repatriate all high activity DSRSs back to their countries of origin. However, this option is not always available. In some cases, the countries of origin are not

[6] Examples of such domestic programmes are the Off-site Source Recovery Programme (OSRP) *(http://osrp.lanl.gov/)* in the United States of America and the disused source management programme implemented by the public utility group for the management of high activity disused sources (GIP sources HA) and the French Atomic energy Commission (CEA) in France.

willing to take back DSRSs, the fees charged are too high, there is a lack of transport containers, there is insufficient infrastructure or there are transport problems because some shippers and ports are reluctant or unwilling to handle DSRSs. The IAEA is working to address all these constraints and many countries are supporting this effort through the voluntary contribution of expertise and resources.

V–3.2. Disposal options for DSRS

Proven long-term storage technologies are available for DSRSs. However, numerous factors may severely disrupt storage records and storage systems and final disposal of DSRS is a way to avoid this risk.

The disposal of DSRS in engineered near surface repositories is technically viable and has been applied in some countries where the quantity of other types of low and intermediate level radioactive waste justified establishing such facilities. However, even in many of these countries, the disposal of DSRS has been halted due to changes in regulatory practices and DSRS have accumulated in storage facilities. In countries without long-lived radioactive waste other than DSRS, the volume of DSRS is too small for such disposal facilities to be economically justifiable, and none has yet been built.

An alternative option for small scale disposal is the use of boreholes.[7] Over the past few years, the IAEA, in conjunction with African Member States, has developed a borehole disposal concept (BDC) that is appropriate for the relatively small amounts and activity levels of the sources that one can realistically expect to find in some developing countries, as well as for their limited resources. The BDC is illustrated in Fig. VI–7. It comprises a borehole with a diameter of 150 to 260 mm that is drilled to a depth of between 30 and 100 metres. The depth of the borehole would be dependent on a site-specific safety assessment. This disposal system is intended to both isolate the waste from the accessible environment and mitigate the consequences of any accident that releases radionuclides. The generic long-term safety analyses that have been conducted have demonstrated

[7] Examples of borehole disposal include the former Soviet Union's disposal of sources in shallow boreholes and the USA's disposal, during the 1980s, of sources at the Nevada Test Site in wide diameter boreholes 36 metres deep. Boreholes have also been used in Australia at the Mt. Walton East facility and in South Africa for high activity sources.

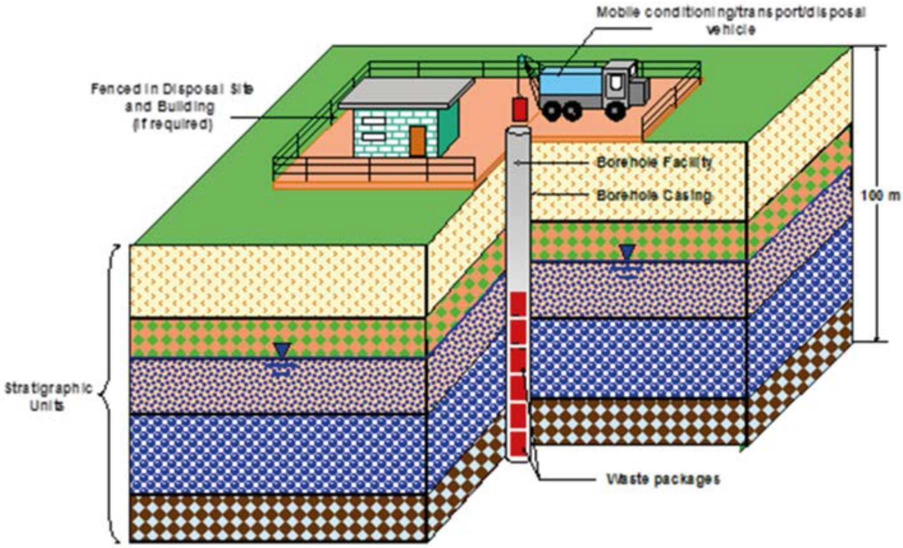

FIG. VI–7. The borehole disposal concept.

that a high degree of safety can be achieved by the BDC for a variety of scenarios and inventories of radioactive sources.[8]

VI–4. Conclusion

The widespread use of SRSs worldwide in industry and medicine provides major benefits to human society. However, the use of radioactive materials should be planned and addressed in a holistic manner by all stakeholders involved in any part of the life cycle of SRSs. While it is important to harness the power of radiation for various beneficial applications, it is also imperative, for safety reasons, to make the necessary arrangements to manage the entire life cycle of the SRSs thus used.

Users should identify appropriate routes for the disposal of DSRSs before they acquire and use radioactive sources. In many countries, the identification of a source management strategy is an essential prerequisite for receiving regulatory authorization to start operating a facility that uses radioactive sources.

[8] The Nuclear Energy Corporation of South Africa (Necsa), contracted by the IAEA, has carried out related project development and demonstration activities since 1996. The project has looked into the technical feasibility, safety and economic viability of the BDC under the social, economic, environmental and infrastructural conditions currently prevalent in Africa.

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IAEA

www.iaea.org

International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Telephone: (+43-1) 2600-0
Fax: (+43-1) 2600-7
Email: Official.Mail@iaea.org