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Nuclear Technology Review 2012

Report by the Director General

Summary

- In response to requests by Member States, the Secretariat produces a comprehensive Nuclear Technology Review each year. Attached is this year's report, which highlights notable developments principally in 2011.
- The *Nuclear Technology Review 2012* covers the following areas: power applications, advanced fission and fusion, accelerator and research reactor applications, nuclear technology in food and agriculture, human health, environment, water resources, and radioisotope production and radiation technology. Additional documentation associated with the *Nuclear Technology Review 2012* is available on the Agency's website[1] in English on developing alternatives to gamma irradiation for the Sterile Insect Technique (SIT); imaging for breast cancer diagnosis and treatment, radiation technology applications in mining and mineral processing, technology options for a country's first nuclear power plant, the role of research reactors in introducing nuclear power, and the use and management of sealed radioactive sources.
- Information on the IAEA's activities related to nuclear science and technology can also be found in the IAEA's Annual Report 2011 (GC(56)/2), in particular the Technology section, and the Technical Cooperation Report for 2011 (GC(56)/INF/4).
- The document has been modified to take account, to the extent possible, of specific comments by the Board of Governors and other comments received from Member States.

[1] http://www.iaea.org/About/Policy/GC/GC56/Agenda/index.html

Nuclear Technology Review 2012[2]

Report by the Director General

Executive Summary

1. 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.

2. 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.

3. 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 accident, to consider the lessons that needed to be learned, to help launch a process to enhance nuclear safety throughout the world

[2] Starting with the *Nuclear Technology Review 2012*, the part of the report covering nuclear sciences and applications will focus on those thematic areas where there have been the most significant developments since previous years. With a reduced number of thematic areas, significant trends and developments are described in greater detail. This process of focusing will be continued in the 2013 version of the NTR.

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.

4. 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.

5. 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.

6. 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.

7. In 2011, the Food and Agriculture Organization 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.

8. The globalisation 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 cesium-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.

9. The Fukushima 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.

10. In the area of environmental protection, the Fukushima 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.

11. 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.

12. 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.

13. 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.

14. 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.

15. 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.

16. 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.

17. 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 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

1. 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)[3] (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.

2. 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.

3. 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.

4. 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.

5. 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 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

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[3] A GW(e) equals one thousand million watts of electrical power.

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 nuclear reactor 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.

6. 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.[4]

7. 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 Russia’s Atomstroyexport (ASE). In November 2011, Bangladesh signed an intergovernmental agreement with Russia 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.

8. 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

[4] 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.

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

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	1816	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
IRAN, ISLAMIC REPUBLIC OF	1	915			0.1		0	4
JAPAN	50	44 215	2	2 650	156.2	18.1	1546	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	1058	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
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	1495	2
UNITED STATES OF AMERICA	104	101 465	1	1 165	790.4	19.3	3707	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.

A.2. Projected Growth for Nuclear Power

9. 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.

10. 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.

11. 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.

12. Other regions with substantial nuclear power programmes are Eastern Europe (including the Russian Federation), 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.

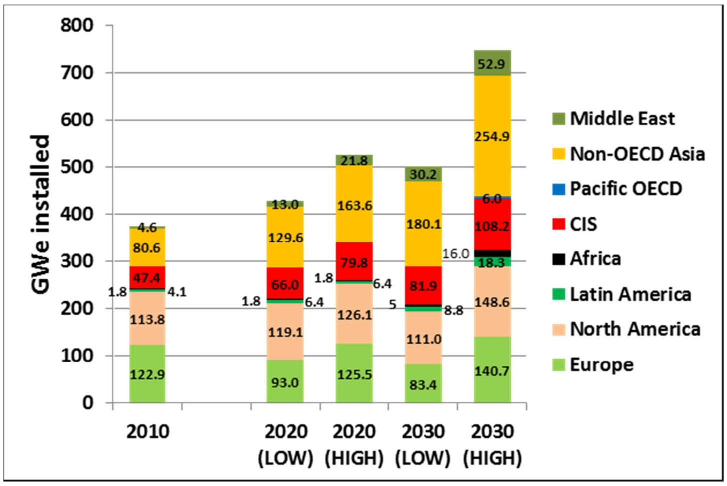

FIG. A-1. Development of regional nuclear generating capacities 2010–2030, low and high 2011 IAEA projections.

13. 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 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.

14. 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.

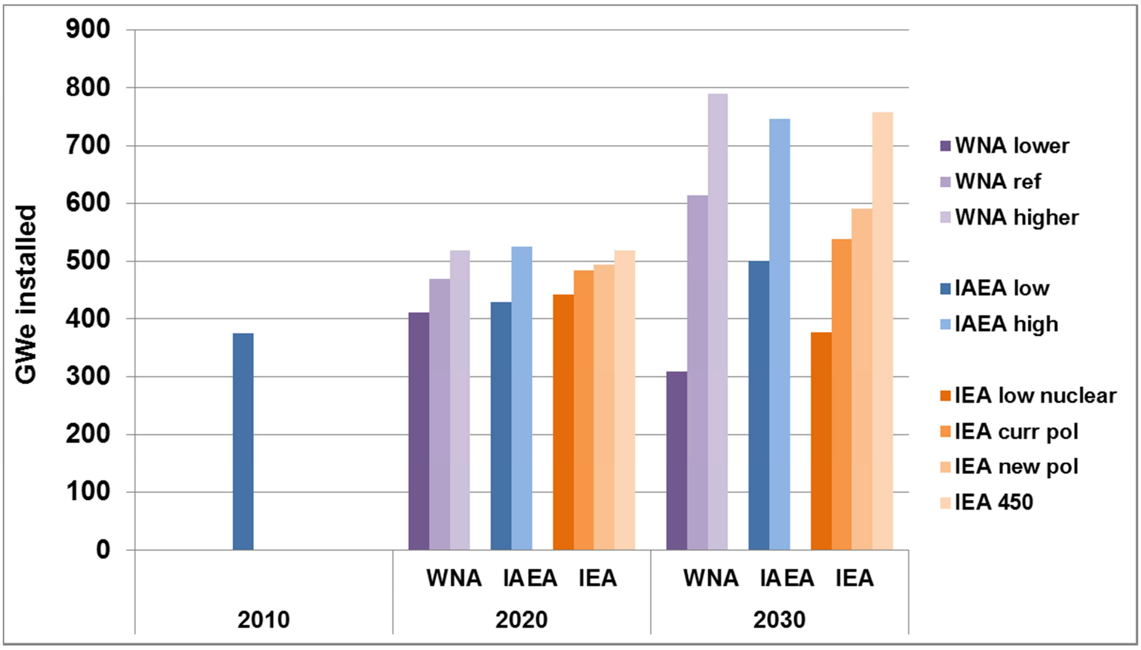

FIG. A-2. Comparison of nuclear power projections by the IAEA (blue), the World Nuclear Association (WNA; purple) and the International Energy Agency's "World Energy Outlook 2011" (IEA; orange).

15. 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 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).[5] 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.

A.3. Fuel Cycle[6]

A.3.1. Uranium resources and production

16. 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.

17. 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.

18. Additional resources were reported in 2011 for many uranium deposits in Africa — namely in Botswana, the Islamic Republic of 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 Columbia, Guyana, Peru, and Paraguay.

19. 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.

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[5] *The Global Nuclear Fuel Market: Supply and demand 2011-2030*, WNA, London, 2011.

[6] 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 GovAtom/GC website and at www.iaea.org/NuclearFuelCycleAndWaste.

20. 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 commercialisation of the AHWR is not expected before 2030.

21. 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.

22. In 2010, uranium production worldwide surpassed 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.

23. In September 2011, commercial production was reported for the first time at the in-situ leaching[7] mine at Honeymoon in Australia. Once fully operational, the 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.

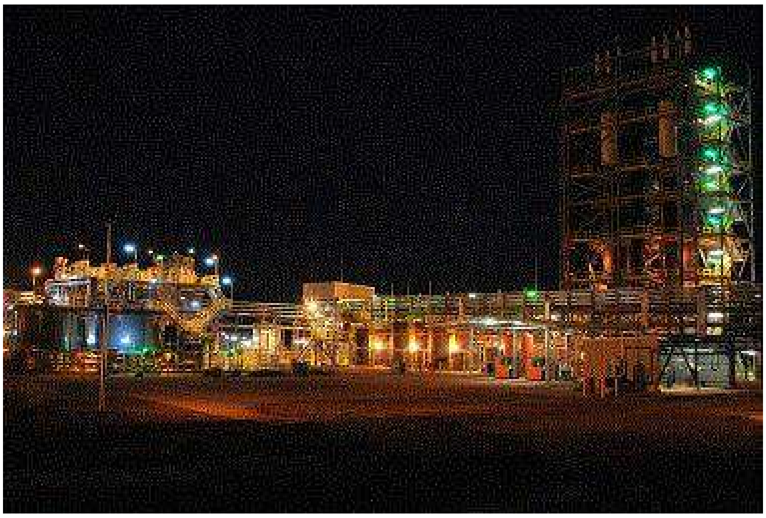

FIG. A-3. Honeymoon uranium mine, Australia, started commercial production in September 2011.

24. 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

[7] 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 pregnant 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.

(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).

25. 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

26. 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) [8]is in the range of 59 000 to 65 000 t U/year.

27. 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.

28. 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.

29. 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.

30. 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 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.

31. In June 2011, an agreement was reached on new global terms of trade for uranium enrichment and spent fuel reprocessing by forty-six 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

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[8] 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.

citations by international nuclear regulators for safeguard deficits, compliance with IAEA safeguards agreements and adherence to international safety standards.

32. 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).

33. 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.

34. 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.

35. 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, 32 thermal reactors currently use MOX fuel.

Assurance of Supply

36. 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.

37. 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.

38. 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).

39. 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.

40. 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

41. 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.

42. 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.

43. 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).

44. 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

45. 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)[9], 13.9 million m^3 of long lived, low and intermediate level waste (LILW–LL), and 423 000 cubic m^3 of high level waste (HLW) (see Table A-2).

Table A-2. Global estimate of radioactive waste inventory for 2010 (most recent data)[10]

Waste class[11]	**Storage**[12] (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.[13]

46. 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

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

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.

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

48. 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.

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

50. 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.

51. 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.

52. 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.

53. 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.

54. 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.

55. 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.

56. 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.

57. 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.

58. In Russia, 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.

59. 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.

60. A new radioactive waste disposal facility was opened in November 2011near 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.

61. 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.[14] The final report was issued in January 2012.

62. 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.

63. 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 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

64. 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

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

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 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.

65. 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 waste by pre-treatment followed by vitrification.

Radioactive waste generated by the Fukushima Daiichi accident

66. Radioactive waste generated by the Fukushima 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.

67. 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.

68. 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.

69. 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.

70. 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

71. 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.

72. 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.

73. 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.

74. 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[15]

75. 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.

76. A Ministerial Conference on Nuclear Safety was convened by the Agency in June 2011 discuss an initial assessment of the Fukushima 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.

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

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[15] Additional information on Nuclear Safety can be found in the Nuclear Safety Review 2012 or in the IAEA Annual Report.

78. 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.[16]

79. 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.

80. 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 Information System (PRIS) database.[17] 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 Figure 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 2012.

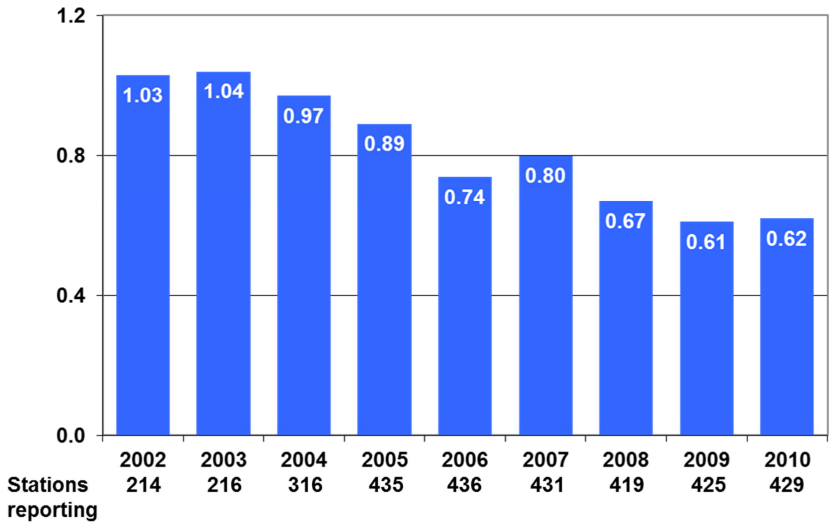

FIG. A- 4. Total number of unplanned scrams, including both automatic and manual scrams, that occur per 7000 hours of critical power reactor operation (Source: IAEA).

[16] 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.

[17] http://prisweb.iaea.org

B. Advanced Fission and Fusion

81. 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

82. 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.

83. In China, 27 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.

84. 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.

85. 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.

86. 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.

87. 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.

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

89. 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

90. 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.

91. 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.

92. 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.

93. 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.

94. 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.

95. 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.

96. 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.

97. 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 Belgian Nuclear Research Centre (SCK•CEN)'s laboratories in Mol.

B.1.3. Gas cooled reactors

98. 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.

99. 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.

100. 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.

101. 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.

102. 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)[18]

103. 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.

104. 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).

105. 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.

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

107. 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).

108. 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.

109. 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.

110. 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.

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[18] A booklet entitled *Status of Small and Medium Sized Reactor Designs* has been published by the Agency and can be downloaded here: 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.

111. 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.

112. 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.

113. 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.

114. 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).

115. In Slovakia, two units of VVER-440 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.

116. 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.

117. 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

118. 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 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.[19]

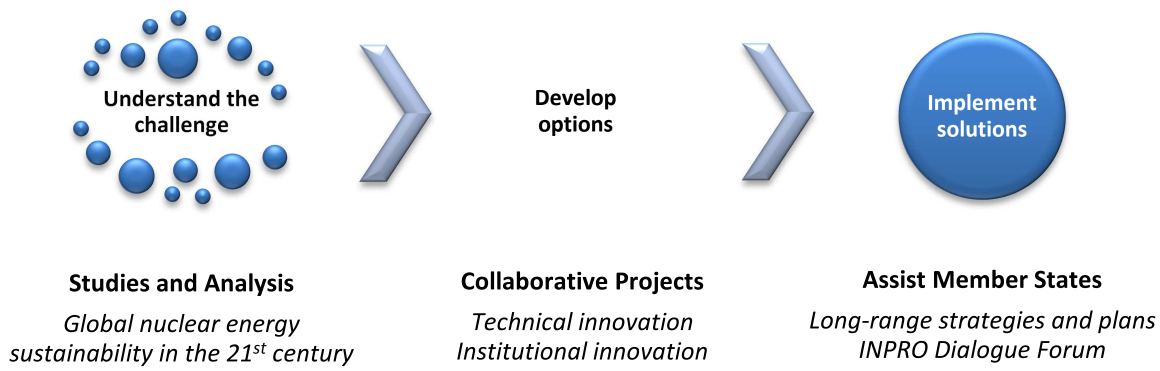

FIG. B-1. Global nuclear energy sustainability and INPRO's contribution.

119. 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.

120. 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 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.[20]

121. 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

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

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

reconfirmed the cooperation between GIF and INPRO, in particular on proliferation resistance evaluation methods and safety aspects of SFRs.

B.2. Fusion

122. 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.

123. 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 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.

124. 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.

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

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

C. Accelerator and Research Reactor Applications

C.1. Accelerators

126. 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.

127. 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.

128. 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.

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

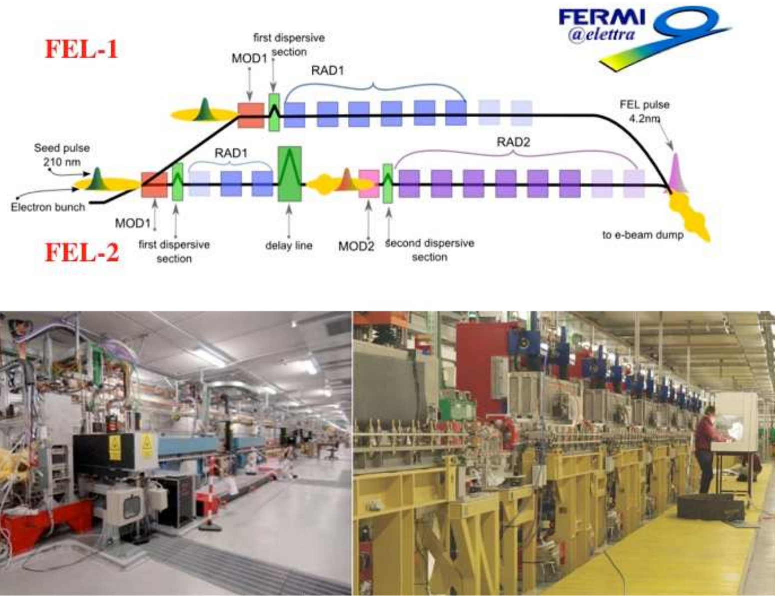

FIG. C-1. Schematic diagram of the FERMI free electron laser and inside views of the facilities (Photo credit: FERMI@Elettra).

130. 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

131. 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.[21] 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.

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[21] Additional information can be found in the appropriate attachment to the *Nuclear Technology Review 2012* on the GovAtom/GC website.

132. 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.[22] 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.

133. 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 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.

134. 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

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

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.

135. 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.

136. 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.

137. 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.

138. 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

139. 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.

140. 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.

141. 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.

142. In response to the Fukushima 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

143. 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

144. Recent studies[23] 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

145. 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

[23] Van den AKKER, J. et al.: Salinity Effects from Evaporation and Transpiration under Flood Irrigation. Journal of Irrigation and Drainage Engineering **137** (2011):1-11

represents a breakthrough.[24] This 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.

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).

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

146. Recent studies[25,26] 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[27] in that they are fallout radionuclides originating from nuclear weapon testing and normally present in most soils, so

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[24] 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.

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

[26] HOO, W.T et al. 2011: Using fallout plutonium as a probe for erosion assessment. J. Environ. Radio. **102** (2011), 937-942.

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

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

147. 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.[28] 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 — were also developed and implemented at a large scale in areas affected by the accident.

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).

148. 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

[28] Alexakhin, R.M., "Remediation of areas contaminated after radiation accidents and incidents", Remediation of contaminated environments (Voigt, G. and Fesenko, S,. Eds.), Elsevier, Amsterdam (2009) 177-222, Ch. 4.

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[29] and in some follow-up reviews by the Agency and other international organizations.[30]

149. The Fukushima 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.

150. 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).

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).

151. 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.).

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

[30] Fesenko, S.V., Alexakhin, R.M., Balonov, M.I., Bogdevich, I.M., Howard, B.J., Kashparov, V.A., Sanzharova, N.I., Panov, A.V., Voigt, G., Zhuchenko, Y.M., An extended review of twenty years of countermeasures used in agriculture after the Chernobyl accident, Sci. Total. Environ. **383** (2007) 1-24.

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

152. 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 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[31]

153. Sterilization of insects as part of insect pest control programmes has traditionally used cobalt-60 or cesium-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.

154. 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 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.

[31] Additional information is available in the appropriate attachment to the *Nuclear Technology Review 2012* on the GovAtom/GC website.

E. Human Health

E.1. Nutrition

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

155. 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.[32] Current standards for assessing a child's growth are primarily based on weight and length or height (WHO, Geneva, 2006[33] and 2011[34]). 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.

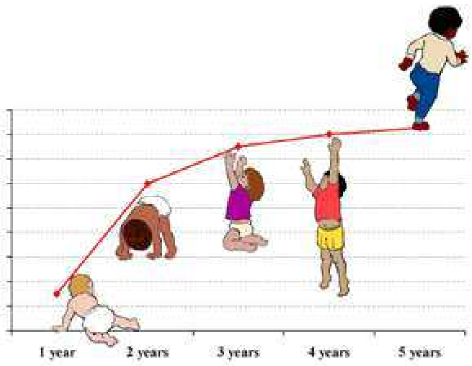

FIG. E.1. Image taken from WHO Child Growth Standards showing the development of a child's growth in the first five years of its life. These standards are based on data (height, weight, age) from approximately 8500 healthy breastfed infants and children from widely different ethnic backgrounds and cultural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

156. 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

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[32] See the 1,000 Days website: http://www.thousanddays.org/.

[33] 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. Geneva: World Health Organization (WHO), 2006. See: http://www.who.int/childgrowth/standards/technical_report/en/.

[34] 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/.

and are at greater risk of non-communicable diseases during later adult life.[35] 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).

157. 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.[36]

158. 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.

159. 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.[37] 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

160. 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.

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[35] 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.

[36] 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. and 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

[37] International Atomic Energy Agency, Body Composition Assessment from Birth to Two Years of Age (in press).

161. 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.

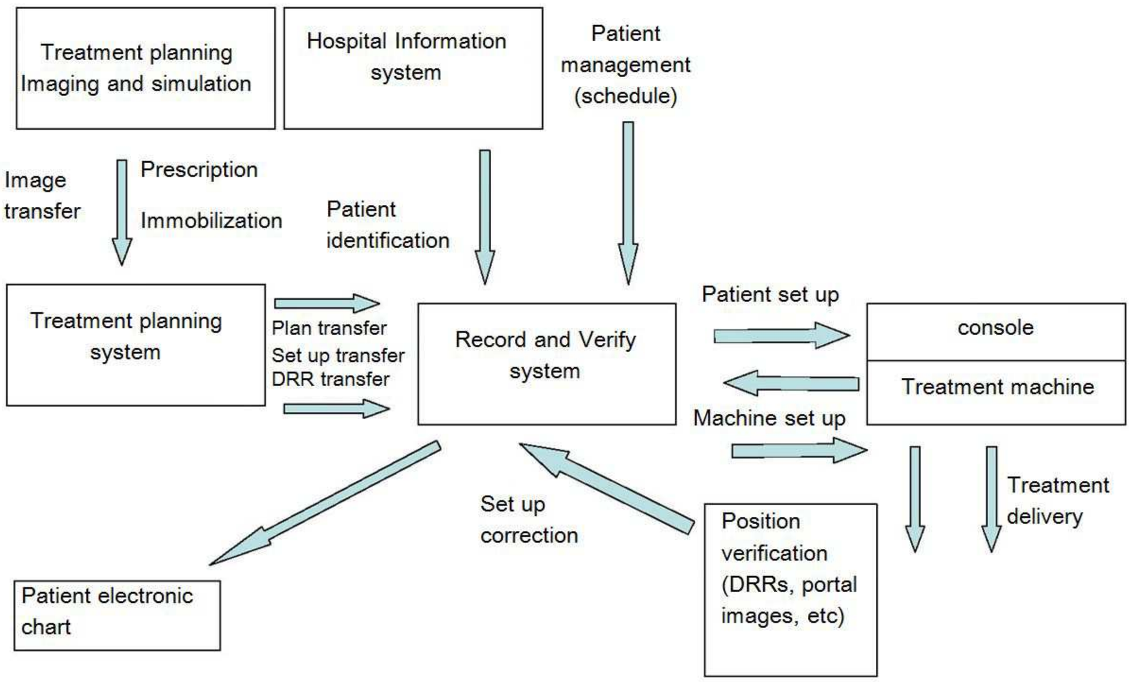

FIG. E.2. Illustration of typical data exchanges between the RVS and other pieces of equipment in a modern radiotherapy department. Different manufacturers may propose different solutions, offering a greater or lesser degree of integration of the various components.

E.2.2. Current trends in cancer management with radiotherapy

162. 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.[38]

163. 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-

[38] 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.

dimensional conformal radiotherapy (3D-CRT); a modality in which the volume treated conforms closely to the shape of the tumour volume.

164. ***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.[39]

165. ***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.[40]

166. ***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.[41] The main advantage of this method is the relatively short overall irradiation time.

167. ***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.[42] 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.

168. ***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.[43] 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.

169. ***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.

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[39] GALVIN, J.M., EZZEL, G., EISBRUCH, A., 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.

[40] VAN HERK, M., Different styles of image guided radiotherapy, Seminars in Radiation Oncology, 17 4 (2007) 258–267.

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

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

[43] BOURLAND, J.D., “Stereotactic radiosurgery”, Clinical Radiation Oncology, 2nd edn (GUNDERSON, L.L., TEPPER, J., Eds), Elsevier Churchill Livinstone, (2007) 151 Ch. 6.

170. ***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.

171. ***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 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.

172. ***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.[44]

173. ***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.

174. 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.

175. 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, Tanzania, Vietnam and Yemen) have received

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

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[45]

176. 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 socio-economic 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.

177. 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.

178. Apart from radiologic 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 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.

179. 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 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*).

180. 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 (3D 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.

181. 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

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[45] Additional information is available in the appropriate attachment to the *Nuclear Technology Review 2012* on the GovAtom/GC website.

called "dose-painting") allows for beneficial dose distribution: high dose to the tumour and low dose to normal organs (heart, lung, skin, etc.).

182. 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 (4D 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.[46]

183. 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 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.

184. 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[47,48]. 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[49,50,51,52]. 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

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

[47] SINGLETARY S.E., ALLRED, C., ASHLEY, P., et al., Revision of the Amercian Joint Committee on Cancer Staging System for breast cancer. J Clin Oncol 2002; 20 (17): 3628-3636.

[48] GREENE, F.L., PAGE, D.L., FLEMING, I.D., et al (eds), AJCC Cancer Staging Manual, Sixth Edition, 2002; New York, NY, Springer-Verlag.

[49]. TAGHIAN, A.G., JEONG, J.H., MAMOUNAS, E.P., 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 2006; 24 (24): 3927-3932.

[50] TAGHIAN, A., JEONG, J., MAMOUNAS, E. 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 2004; 22 (21): 4247-4254.

[51] 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 2006; 24 (15): 2268-2275.

[52] RECHT A., GRAY, R., DAVIDSON N.E., 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 1999; 17 (6): 1689-1700.

use of systemic therapy. The time to loco-regional recurrence has been reported to be as short as 3 to 12 months[53], but most loco regional recurrences occur within 3 years.

185. 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.

F. Environment

F.1. Rapid radio-analytical methods can make a difference in assessing radioactive pollution in emergency situations

186. The Fukushima 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.

187. 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.

188. 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 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.

[53] 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. African Journal of Medicine & Medical Sciences 2002; 31(4): 345 - 7.

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.

189. 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.

190. 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.

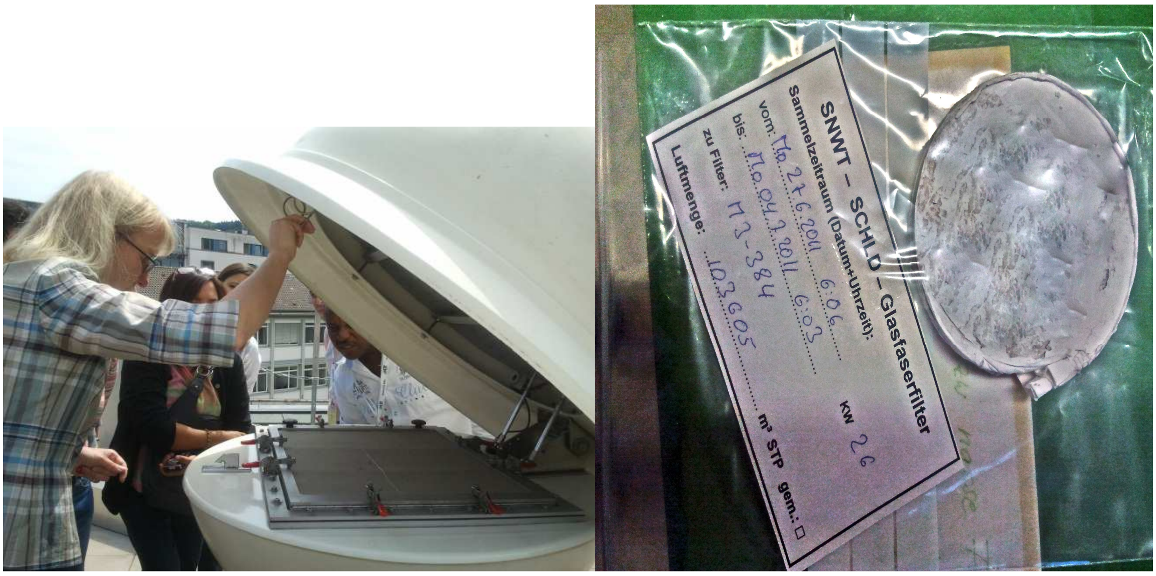

FIG. F.1. Large volume aerosol collector operated by the Federal Office for Radiation Protection in Salzgitter, Germany, and aerosol filter compacted for immediate gamma spectrometric counting - being demonstrated to participants in the Agency's Interregional Advanced Training Course on Marine Radioactivity: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

191. The Fukushima 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 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

192. 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 [54], 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.

193. 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 geographic 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

194. 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 (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

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

based on the same technology is expected to accelerate, thereby facilitating the use of these isotopes in the study of groundwater and surface water.

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).

G.2. Groundwater dating

195. 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.

196. 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[55] are increasingly being used, improving flow and transport groundwater models. Isotope hydrology offers the potential to obtain the

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

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.

H. Radioisotope Production and Radiation Technology

H.1. Radioisotopes and radiopharmaceuticals

H.1.1. Recent developments in generator produced PET radionuclides

197. 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

198. 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.

199. 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

200. 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

201. 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.

202. 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

203. 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.

204. 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 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.

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

H.2.3. Electron beam technology for producing bioethanol from agro industrial residue

205. 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.[56] This could significantly reduce CO_2 emissions while enhancing energy security, without harming food security if agro-industrial 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 agro-industrial 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.

206. 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.

207. 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.

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[57]

208. 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

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

[57] Additional information is available in the appropriate attachment to the *Nuclear Technology Review 2012* on the GovAtom/GC website.

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.

209. 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.

210. 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.