NUCLEAR TECHNOLOGY REVIEW

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Atoms for Peace: The First Half Century
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NUCLEAR TECHNOLOGY REVIEW 2007

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

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EXECUTIVE SUMMARY

The year 2006 saw increasing activities in the field of nuclear power. Significant plans for expansion were announced in some countries and plans for introducing nuclear power in some others. The year began with announcements by both the Russian Federation and the United States of America of international fuel cycle proposals in anticipation of a substantial expansion of nuclear power worldwide. In January, Russian President Vladimir Putin outlined a proposal to create "a system of international centres providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the IAEA". In February, the USA proposed a Global Nuclear Energy Partnership to develop advanced recycling technologies that would not separate pure plutonium; international collaboration in supplying fuel for States which agree not to pursue enrichment and reprocessing; advanced reactors to consume recycled spent fuel while providing energy; and safe and secure small reactors suited to the needs of developing countries.

New medium-term projections by the IAEA and the International Energy Agency present a picture with opportunities for substantial nuclear expansion, but still with notable uncertainty. A number of countries have announced plans for significant expansion: China, India, Japan, Pakistan, the Russian Federation and the Republic of Korea. Announcements of planned license applications by US companies and consortia mentioned approximately 25 new reactors. Two site preparation applications were submitted in Canada. A major energy review by the United Kingdom concluded that new nuclear power stations would make a significant contribution to meeting the UK's energy policy goals. Utilities from Estonia, Lithuania and Latvia launched a joint feasibility study of a new nuclear power plant to serve all three countries, and Belarus, Egypt, Indonesia, Nigeria and Turkey made announcements of steps they are taking toward their first nuclear power plants.

Worldwide at the end of 2006, there were 435 nuclear power reactors in operation, totalling 370 GW(e). In the course of the year two new reactors were connected to the grid and eight were retired, resulting in a small net growth in global nuclear generating capacity during 2006, taking the increased rating of existing reactors into account, of 1443 MW(e). There were three construction starts plus the resumption of active construction at one plant in the Russian Federation, for a total of 23 641 MW(e) under construction at the end of the year.

Driven partly by rising expectations for nuclear power, uranium spot prices continued to rise in 2006, to nine times their historic 2000 low. Annual exploration expenditures have increased more than three-fold since 2001.

Brazil opened its new Resende enrichment facility, and construction started at the US National Enrichment Facility and at the Georges Besse II enrichment plant in France. Final testing for commissioning Japan's new Rokkasho reprocessing plant began in March.

The world's only operating geological repository, the Waste Isolation Pilot Plant in the USA, received its first recertification from the US Environmental Protection Agency since opening in 1999. France passed new legislation setting goals to apply for a licence for a deep geological repository with the aim of opening it by 2025, and for a prototype reactor by 2020 to, among other tasks, test transmutation of long-lived radioisotopes. The Swedish nuclear fuel and waste management company SKB filed an application for an encapsulation plant in Oskarshamn, the first step towards final disposal.

Concerning advanced reactor designs, Westinghouse's AP-1000 design which has passive safety systems was certified by the US Nuclear Regulatory Commission (NRC) in 2006. The Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) grew to 28 members with the addition of Belarus, Japan, Kazakhstan and Slovakia, and the Generation IV International Forum (GIF) grew to thirteen members with the addition of China and Russia. INPRO moved into a second phase following completion of a methodology that Member States can use to evaluate and select innovative nuclear systems (INS) for development. INPRO's Phase 2 explores innovative institutional and infrastructural approaches to introduce INS, joint assessments of INS and collaborative projects among Member States. GIF members signed four 'system arrangements' in 2006 covering collaboration on sodium-cooled fast reactor systems, gas-cooled fast reactor systems, very high temperature gas-cooled reactor systems, and supercritical water-cooled reactor systems. The agreements provide the framework for GIF member countries to participate in collaborative research and development on various technologies.

Increasing demands are being made for more accurate atomic and nuclear databases to support nuclear applications in research, energy and in the production of therapeutic radionuclides in nuclear medicine. Radioisotopic applications in healthcare are increasing, with growing requirements for positron emitters for use in positron emission tomography (PET).

Interest in radiation technology was shown by three major international meetings, addressing radiation processing; radiation chemistry; and polymer production and usage. Radiation grafting of polymers is offering lower cost manufacturing techniques for a wide range of uses, from fuel cells to medicine and biotechnology.

Nuclear and isotopic techniques continue to play important roles in many aspects of food and agriculture. Isotopes are increasingly used for tracking soil pollutants, with particular use being made of fallout radionuclides from the weapons testing era. Mutation induction techniques for plant breeding are benefiting from the improved methodology for genome sequencing, creating possibilities for increasing the number of crop varieties that are tolerant to harsh conditions. Livestock productivity is being improved through the use of stable isotopes for a better understanding of animal nutrient uptake and optimization of feeding regimes. The use of the sterile insect technique is expanding, and some successes and new facilities for sterile fly production are reported.

Advances in nuclear cardiology are being made through new imaging techniques which now allow disease assessment in very early stages. These same imaging techniques combined with sophisticated computing are promoting rapid developments in radiotherapy, giving, amongst other advantages, the ability of accurate dose delivery to organs that move when the patient breathes, and a reduction in the doses received by adjacent healthy tissues. In the field of nutrition, programmes using stable isotopic techniques are benefiting from increased access to analytical equipment which can be used for assessments of body composition and for human milk intake in infants.

Improved understanding of the water cycle is a key element in sustainable water resource management. Measurement of isotopic contents in waters of different origins (precipitation, groundwater, etc.) helps with the understanding of the water cycle and climate, and there are increasing national efforts to broaden the availability of isotopic data. These efforts will further strengthen the Global Network for Isotopes in Precipitation, which provides a tool to interpret national or local isotope data.

In environmental studies, radiotracers are providing cost effective tools for analysing the take up by marine organisms of toxic metals, and thus contributing to seafood safety studies and quality improvements. Studies of air pollutants to determine their composition and sources are also using nuclear techniques, such as X-ray fluorescence and neutron activation analyses, and measurements of the naturally occurring radioactive gas radon are being increasingly used to study the atmosphere, contributing to the Global Atmosphere Watch programme of the World Meteorological Organization.

A. POWER APPLICATIONS

A.1. Nuclear Power Today

Worldwide there were 435 nuclear power reactors in operation at the end of 2006, totalling 370 GW(e) of generating capacity (see Table A-1). In 2006 nuclear power supplied about 15% of the world's electricity.

Two new reactors were connected to the grid in 2006, one in China and one in India. This compares with four new connections in 2005 (plus the reconnection of one laid-up reactor) and five new connections in 2004 (plus one reconnection). There were eight nuclear power reactor retirements in 2006: two in Bulgaria, four in the UK, one in Slovakia and one in Spain. This compares to two retirements in 2005 and five in 2004. Taking uprates of existing reactors into account, the effect was a small net increase in global nuclear generating capacity during 2006 of 1443 MW(e).

There were three construction starts in 2006: Lingao-4 (1000 MW(e)) and Qinshan II-3 (610 MW(e)) in China and Shin Kori-1 (960 MW(e)) in the Republic of Korea. In addition, active construction resumed at Beloyarsk-4 in Russia.

The three construction starts in 2006 and the resumption of construction at Beloyarsk-4 compare to three construction starts in 2005 plus resumed construction at two reactors. In 2004 there were two construction starts plus resumed construction at two other reactors.

Current expansion, as well as near-term and long-term growth prospects, remain centred in Asia. As shown in Table A-1, of the 29 reactors under construction, 17 were in Asia. By the end of the year 26 of the last 36 reactors to have been connected to the grid were in Asia.

In the United States of America the Nuclear Regulatory Commission (NRC) approved eight more licence renewals of 20 years each (for a total licensed life of 60 years for each nuclear reactor), bringing the total number of approved licence renewals to 47 at the end of the year. In the Netherlands, the government granted a 20-year extension to the Borssele nuclear power plant for a total licensed lifetime of 60 years. The government also set conditions for new nuclear plants, a shift from the country's earlier nuclear power phase-out policy. The French Nuclear Safety Authority (ASN) conditionally cleared Électricité de France's twenty 1 300 MW(e) pressurized water reactors for an additional ten years of operation, for a total currently licensed period of 30 years. In Canada, Point Lepreau received a three-year licence renewal through 2011.

TABLE A-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 1 January 2007)[a]

Country	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2006		Total Operating Experience through 2006	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
Argentina	2	935	1	692	7.2	6.9	56	7
Armenia	1	376			2.4	42.0	32	8
Belgium	7	5 824			44.3	54.4	212	7
Brazil	2	1 901			13.0	3.3	31	3
Bulgaria	2	1 906	2	1 906	18.2	43.6	141	3
Canada	18	12 610			92.4	15.8	528	1
China	10	7 572	4	3 610	51.8	1.9	66	7
Czech Republic	6	3 323			24.5	31.5	92	10
Finland	4	2 696	1	1 600	22.0	28.0	111	4
France	59	63 260			429.8.	78.1	1 523	2
Germany	17	20 339			158.7	31.8	700	5
Hungary	4	1 755			12.5	37.7	86	2
India	16	3 577	7	3 112	15.6	2.6	267	7
Iran, Islamic Republic of			1	915				
Japan	55	47 587	1	866	291.5	30.0	1 276	8
Korea, Republic of	20	17 454	1	960	141.2	38.6	279	8
Lithuania	1	1 185			7.9	72.3	40	6
Mexico	2	1 360			10.4	4.9	29	11
Netherlands	1	482			3.3	3.5	62	0

TABLE A-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 1 January 2007)[a] (cont.)

Country	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2006		Total Operating Experience through 2006	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
Pakistan	2	425	1	300	2.6	2.7	41	10
Romania	1	655	1	655	5.3	9.0	10	6
Russian federation	31	21 743	5	4 525	144.6	15.9	901	4
Slovakia	5	2 034			16.6	57.2	118	7
Slovenia	1	666			5.3	40.3	25	3
South Africa	2	1 800			10.1	4.4	44	3
Spain	8	7 450			57.4	19.8	245	6
Sweden	10	9 097			65.1	48.0	342	6
Switzerland	5	3 220			26.4	37.4	158	10
Ukraine	15	13 107	2	1 900	84.9	47.5	323	6
United Kingdom	19	10 965			69.4	18.4	1 400	8
United States of America	103	99 257			788.3	19.4	3 188	2
Total[b, c]	435	369 682	29	23 641	2 660.9	15%	12 599	1

[a] Data are from the Agency's Power Reactor Information System (*http://www.iaea.org/programmes/a2/index.html*)

[b] Note: The total includes the following data in Taiwan, China:

— 6 units, 4921 MW(e) in operation; 2 units, 2600 MW(e) under construction;

— 38.3 TW·h of nuclear electricity generation, representing 19.5% of the total electricity generated in 2006;

— 152 years, 1 month of total operating experience at the end of 2006.

[c] The total operating experience includes also shutdown plants in Italy (81 years) and Kazakhstan (25 years, 10 months).

A.2. Projected Growth for Nuclear Power

In 2006, updated projections of nuclear power expansion through 2030 were published by the IAEA[1], and by the International Energy Agency (IEA) in its *World Energy Outlook 2006* (WEO 2006)[2]. The IAEA provides a high and a low projection for nuclear power. The *World Energy Outlook 2006* includes a reference scenario plus an alternative scenario that assumes additional measures to enhance energy security and mitigate carbon dioxide (CO_2) emissions.

In 2006, the IEA published an additional study with seven scenarios extending to 2050[3]. These include a baseline scenario and six 'accelerated technology scenarios (ACTs)'. The accelerated technology scenarios examine technological options to limit or reverse global growth in CO_2 emissions and oil consumption. The three publications thus include, altogether, eleven scenarios. Their projections for nuclear power are summarized in Figure A-1.

In Figure A-1 the IAEA's low projection assumes that no new nuclear power plants are built beyond what is under construction or firmly planned today, and old nuclear power plants are retired on schedule. Nuclear electricity generation in this projection grows to just 3100 TW·h in 2020 (1.1% per year) and remains essentially unchanged through 2030. The IAEA's high projection incorporates additional reasonable planned and proposed nuclear projects beyond those already firmly in the pipeline. It shows steady growth to 5040 TW·h in 2030 (2.6% per year).

These global aggregates mask regional differences, particularly in the low projection. Nuclear electricity generation in Western Europe in the low projection drops by almost 60% between 2005 and 2030, as projected retirements consistently outpace new construction. But nuclear power generation in the Far East grows by 80%, and in Eastern Europe by almost 50%. In the high projection, nuclear generation grows in all regions. In both projections, new construction is greatest in the Far East, Eastern Europe, North America and the Middle East/Southeast Asia, in that order.

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[1] INTERNATIONAL ATOMIC ENERGY AGENCY, *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030*, Reference Data Series No. 1, IAEA, Vienna (July 2006).

[2] INTERNATIONAL ENERGY AGENCY, *World Energy Outlook 2006*, IEA, Paris (2006).

[3] INTERNATIONAL ENERGY AGENCY, *Energy Technology Perspectives: Scenarios & Strategies to 2050*, IEA, Paris (2006).

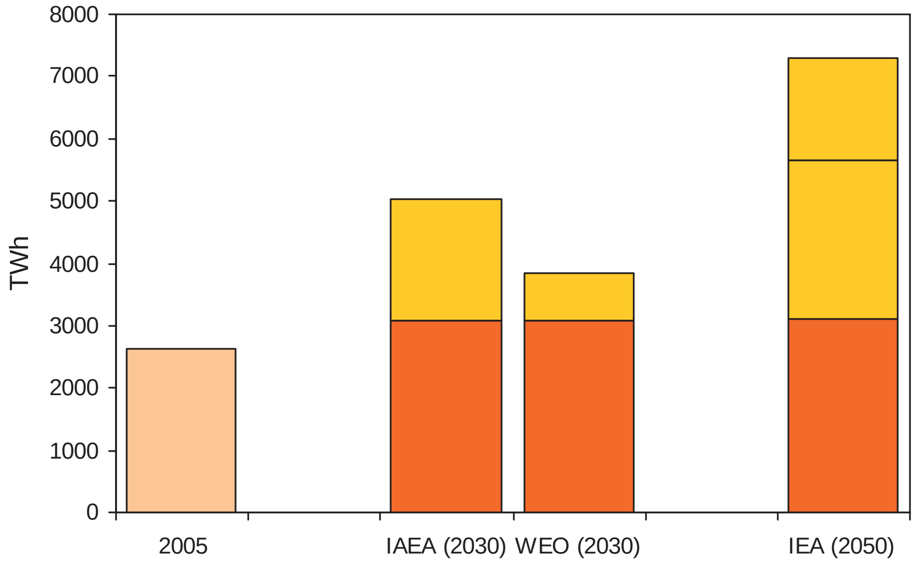

FIG. A-1. Global nuclear electricity generation in 2005 and the ranges of projections for 2030 and 2050 from three studies (dark orange = low, yellow-orange = high, and beige = history).

The WEO reference scenario is a 'business-as-usual' scenario that assumes the continuation of current policies and trends. Projected nuclear electricity generation in this scenario is almost identical to that in the IAEA low projection. The measures in the alternative scenario to enhance energy security and mitigate CO_2 emissions are expected to boost nuclear electricity generation but, as shown in the figure, not enough to match the IAEA's high projection.

For the IEA scenarios in 2050, on the right side of Fig. A-1, the low end of the range is defined by the baseline scenario and a 'low nuclear scenario'. These are essentially extensions of the WEO 2006 reference scenario. The high end of the range is set by the TECH Plus scenario, which assumes accelerated cost reductions for fuel cells, renewables, biofuels and nuclear power. In this scenario, nuclear electricity generation continues to grow to 2050 at essentially the same rate as in the IAEA high projection, and its share of global electricity generation reaches 22%. The other four IEA scenarios cluster around the level of the black bar in the figure, at about 5650 TW·h, or an average growth rate of 1.7% from 2005.

Taken together, these new projections and scenarios present a picture with opportunities for significant nuclear expansion, but still with substantial uncertainty. A number of developments in 2006 suggest that the renewal of interest in nuclear power may reasonably soon lead to increases in construction. These include expansion plans announced in 2006 by Japan and the Russian Federation, as well as previously announced expansion plans of China, India, the Republic of Korea and Pakistan. They include the large number of intended Combined License applications that companies and consortia have announced in the USA, which together cited approximately 25 new reactors. They include two site preparation applications in Canada and the UK energy review's conclusion that new nuclear power stations would make a significant contribution to meeting the UK's energy policy goals. They include a joint feasibility study launched by utilities from Estonia, Lithuania and Latvia of a new nuclear power plant to serve all three countries, and announcements made by Belarus, Egypt, Indonesia, Nigeria and Turkey on steps they are taking toward their first nuclear power plants.

A.3. The Front End of the Fuel Cycle[4]

Driven partly by the renewal of interest in nuclear power, uranium spot prices continued to rise in 2006, reaching $72/lb U_3O_8 by the end of the year, more than ten times higher than their historic low in December 2000.[5] Exploration and mine development have begun to follow suit with exploration expenditures increasing more than three-fold between 2001 and 2005.

The latest estimate of global uranium resources published by the OECD Nuclear Energy Agency (OECD/NEA) and the IAEA in 2006, *Uranium 2005: Resources, Production and Demand*, shows that, while substantial uranium resources are likely to be available, it is estimated that significant mine development will be needed to turn "uranium in the ground into yellowcake in the can". Table A-2 summarizes the potential longevity of the world's conventional uranium resources. For both the current LWR once-through fuel cycle and a pure fast reactor fuel cycle, the table estimates how long conventional uranium resources would last, assuming electricity generation from nuclear power stays at its 2004 level.

Uranium enrichment was a focus of increased international attention in 2006. As with uranium, the price for separative work units (SWUs) climbed,

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[4] More detailed information on IAEA activities concerning the front-end of the fuel cycle is available in relevant sections of the latest IAEA Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/) and at (http://www.iaea.org/OurWork/ST/NE/NEFW/nfcms_home.html).

[5] Most uranium, however, is bought on long term contracts, and between 2000 and 2005 medium and long term uranium prices only increased by 20–40%.

TABLE A-2. Years of Uranium Availability for Nuclear Power[6]

Reactor/fuel cycle	Years of 2004 world nuclear electricity generation with identified conventional resources	Years of 2004 world nuclear electricity generation with total conventional resources	Years of 2004 world nuclear electricity generation with total conventional and unconventional resources
Current once-through fuel cycle with light water reactors	85	270	675
Pure fast reactor fuel cycle with recycling	5000–6000	16 000–19 000	40 000–47 000

increasing by about 45% between 2001 and 2006. Market demands are likely to exceed planned capacity levels after 2013 with the scheduled expiration of the Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons[7], and perhaps sooner in the event of rapid near-term growth in nuclear power plant construction. Significant further capacity additions can be identified beyond those now firmly planned, but particularly if nuclear capacity growth picks up, both SWU prices and uranium prices will continue to rise.

Examples of the increasing attention to uranium enrichment were the official opening of Brazil's Resende facility, the construction starts at the US National Enrichment Facility and at the Georges Besse II enrichment plant in France, the plans announced by Argentina, Australia and South Africa to either revive or explore national enrichment programmes, and General Electric Company's purchase of the rights to Australia's Silex Systems' advanced laser-based uranium enrichment technology. At the same time, President Putin's call

[6] The values in the last row of Table A-2 assume that fast reactors allow essentially all uranium-238 to be bred to plutonium-239 for fuel, except for minor losses of fissile material during reprocessing and fuel fabrication. The resulting values are higher than estimates published in a similar table in *Uranium 2005: Resources, Production and Demand*. The latter estimates assume that not all uranium-238 is bred to plutonium-239 for fuel.

[7] The Agreement provides for weapon grade uranium from dismantled Russian nuclear warheads being diluted and recycled into fuel used mainly by US power plants.

for “a system of international centres providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the IAEA” and the subsequent establishment by the Russian Federation and Kazakhstan of an international uranium enrichment centre at Angarsk, as well as the several additional proposals to assure supplies of enriched uranium in the event of political supply interruptions have demonstrated the will of States to develop new, international approaches to the nuclear fuel cycle.

In this context, an international conference on a “New Framework for the Utilization of Nuclear Energy in the 21st Century: Assurances of Supply and Non-Proliferation” was held as a Special Event at the IAEA’s 50th General Conference. The report of the Chairman of the Special Event recalled the challenge of meeting increasing global energy demands through a possible expansion of the use of nuclear energy, while at the same time minimizing the proliferation risks created by the further spread of sensitive nuclear technology such as uranium enrichment and plutonium reprocessing. The conference reviewed a number of useful suggestions recently put forward regarding new approaches to the nuclear fuel cycle, which aim to establish an assured supply of nuclear fuel, as a back-up measure to the commercial market, in certain situations. The conference considered these recent proposals for assuring supplies of uranium-based nuclear fuel as one stage in a broader, longer-term development of a multilateral framework that could encompass assurance of supply mechanisms for both natural and low enriched uranium and nuclear fuel, as well as spent fuel management. The participants recognized that establishing a fully developed, multilateral framework that is equitable and accessible to all users of nuclear energy, acting in accordance with agreed nuclear non-proliferation norms, is a complex endeavour that would likely require a phased approach. It is expected that the conference’s discussions will be taken into consideration by the Secretariat in developing its proposals for consideration by the IAEA Board of Governors in the course of 2007.

A.4. Spent Fuel and Reprocessing[8]

Annual discharges of spent fuel from the world’s reactors total about 10 500 tonnes of heavy metal (t HM) per year. Two different management strategies are being implemented for spent nuclear fuel. In the first strategy,

[8] More detailed information on IAEA activities concerning spent fuel and reprocessing is available in relevant sections of the latest IAEA Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/), and at http://www.iaea.org/OurWork/ST/NE/NEFW/index.html and http://www-ns.iaea.org/home/rtws.asp.

spent fuel is reprocessed (or stored for future reprocessing) to extract usable material (uranium and plutonium) for new mixed oxide (MOX) fuel. Approximately one third of the world's discharged spent fuel has been reprocessed. In the second strategy, spent fuel is considered as waste and is stored pending disposal. Based on now more than 50 years of experience with storing spent fuel safely and effectively, there is a high level of confidence in both wet and dry storage technologies and their ability to cope with rising volumes pending implementation of final repositories for all high level waste.

As of today, China, France, India, Japan, the Russian Federation and the UK either reprocess, or store for future reprocessing, most of their spent fuel. Canada, Finland, Sweden and the USA have currently opted for direct disposal, although in February 2006, the USA announced a Global Nuclear Energy Partnership (GNEP), which includes the development of advanced recycling technologies for use in the USA.

Most countries have not yet decided which strategy to adopt. They are currently storing spent fuel and keeping abreast of developments associated with both alternatives.

In 2006, final testing for commissioning Japan's new Rokkasho reprocessing plant began in March and is expected to take 17 months. The Rokkasho plant's final product is a MOX powder, which was produced for the first time in November. Commercial-scale production of MOX powder is expected in the second half of 2007. The plant's maximum reprocessing capacity will be 800 tonnes of uranium per year, enough to reprocess 80% of Japan's annual spent fuel production. In China non-radioactive commissioning was completed for the country's first experimental reprocessing plant. Development of new recycling processes is also taking place, e.g. the UREX+ process in the USA to recycle spent nuclear fuel, without separating out pure plutonium, and fabricate the separated transuranic elements into fuel for fast advanced burner reactors.

In 2006, approximately 180 tonnes of civil origin MOX fuel were loaded on a commercial basis in more than 30 pressurized water reactors (PWRs) and two boiling water reactors (BWRs) in Belgium, France, Germany and Switzerland. The share of MOX fuel assemblies in the core varied from 25% to 50%. No substantial increase in MOX fuel requirements is expected until 2010, when Japan plans to start its 'pluthermal' programme to load MOX fuel in 16 to 18 power reactors. In India, some 50 MOX fuel bundles have recently been irradiated in a pressurized heavy water reactor (PHWR 220) on an experimental basis.

Belgonucleaire's MOX fuel plant in Dessel ceased production in August 2006 with decommissioning scheduled for completion by 2013. As a result of this, there remain two significant MOX fuel fabricators in France and the UK.

A.5. Waste and Decommissioning[9]

The Finnish, Swedish and US repository programmes continue to be the most developed, but none is likely to have a repository in operation much before 2020. The world's one operating geological repository is the Waste Isolation Pilot Plant (WIPP) in the USA. Since 1999, it has accepted long lived transuranic waste generated by research and the production of nuclear weapons, but no waste from civilian nuclear power plants. In 2006 the US Environmental Protection Agency approved WIPP's first recertification application, submitted in 2004. Recertification is required every five years. France's new legislation on spent fuel management and waste disposal, which established spent fuel reprocessing and recycling of usable materials as French policy, also established deep-geologic disposal as the reference solution for high level long lived radioactive waste. The legislation sets goals to apply for a licence for a reversible deep geological repository by 2015 and to open the facility by 2025. It also calls for operation of a fourth-generation prototype fast reactor by 2020 to, among other tasks, test transmutation of long lived radioisotopes (see also Section B.1.4). Also in 2006, the UK's Committee on Radioactive Waste Management concluded that the best disposal option for the UK is deep geological disposal, with 'robust interim storage' until a repository site is selected.

In November the Swedish nuclear fuel and waste management company SKB applied to the Swedish nuclear power inspectorate for a permit for an encapsulation plant in Oskarshamn. The encapsulation plant is the first step towards final disposal using the KBS-3 method, in which fuel is encapsulated in copper canisters and deposited in bedrock at a depth of approximately 500 m. A final ruling on the application is not expected until after 2009, when the application for a final deep geological repository is scheduled to be submitted. Site investigations for a final repository are being carried out near Forsmark in Osthammar and in the Laxemar area of Oskarshamn.

Decommissioning was completed in 2006 at the Big Rock Point nuclear power plant site in the USA, and the site returned to green field status. Thus, as of 2006, nine power plants around the world had been completely decommissioned, with their sites released for unconditional use. Seventeen plants have been partially dismantled and safely enclosed, 30 are being dismantled prior to

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[9] More detailed information on IAEA activities concerning waste and decommissioning is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/), and at http://www.iaea.org/OurWork/ST/NE/NEFW/index.html and http://www-ns.iaea.org/home/rtws.asp.

eventual site release, and 30 are undergoing minimum dismantling prior to long term enclosure.

A.6. Additional Factors Affecting the Future of Nuclear Power

A.6.1. Sustainable Development and Climate Change[10]

The UN Commission on Sustainable Development (CSD) first discussed energy at its ninth session (CSD-9) in 2001, and all parties agreed that "the choice of nuclear energy rests with countries." While the 2002 World Summit on Sustainable Development (WSSD) reaffirmed this conclusion, the CSD placed the topic of energy on its agenda for its 14th and 15th sessions. CSD-14 in 2006 was a 'review session' to analyse the impact of energy policy changes and technological advances on progress toward sustainable development. The corresponding 'policy session', CSD-15 in May 2007, did not agree on a new text on energy issues, leaving the decisions reached at CSD-9 and the WSSD as the operative CSD agreements on energy.

The Kyoto Protocol, which entered into force in February 2005, requires most developed countries to limit their greenhouse gas (GHG) emissions in the 'first commitment period', 2008–2012. Different countries have adopted different policies to meet their Kyoto Protocol limits. Not all benefit nuclear power despite its low GHG emissions, but in the longer run, the limits on GHG emissions should make nuclear power increasingly attractive. With respect to emission reductions after the first commitment period, the 11th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP-11) in 2005 decided to start discussions in an ad hoc working group, which has now met three times, in May and November 2006 and in May 2007. Discussions are still in an early phase, and have not yet begun to address specifics such as the current exclusion of nuclear power projects from the clean development mechanism and joint implementation.

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[10] Additional information is available in Annex VI. More detailed information about IAEA activities on energy related aspects of sustainable development and climate change is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/) and at http://www.iaea.org/OurWork/ST/NE/Pess/climate.shtml.

A.6.2. Economics

Nuclear power plants have a ‘front-loaded’ cost structure, i.e. they are relatively expensive to build but relatively inexpensive to operate. Thus existing well-run operating nuclear power plants continue to be a generally competitive profitable source of electricity. For new construction, however, the economic competitiveness of nuclear power depends on the alternatives available, on the overall electricity demand in a country and how fast it is growing, on the market structure and investment environment, on environmental constraints, and on investment risks due to possible political and regulatory delays or changes. Thus economic competitiveness is different in different countries and situations.

In Japan and the Republic of Korea, the relatively high cost of alternatives benefits nuclear power’s competitiveness. In India and China rapidly growing energy needs encourage the development of all energy options. In Europe, high electricity prices, high natural gas prices and GHG emission limits under the European Union Emission Trading Scheme have improved the business case for new nuclear power plants. In the USA the 2005 US Energy Act significantly strengthened the business case for new construction. Previously new nuclear power plants had not been an attractive investment given plentiful low-cost coal and natural gas, no GHG emission limits, and investment risks associated from the lack of recent experience in licensing new nuclear power construction. The provisions of the Energy Act, including loan guarantees, government coverage of costs associated with certain potential licensing delays and a production tax credit for up to 6000 MW(e) of advanced nuclear power capacity, have improved the business case enough to prompt announcements by nuclear firms and consortia of possible Combined License (COL) applications covering approximately 25 possible new reactors in the USA.

A.6.3. Safety[11]

Safety indicators, such as those published by the World Association of Nuclear Operators and reproduced in Figs A-2 and A-3, improved dramatically in the 1990s. However, in some areas improvement has stalled in recent years. Also the gap between the best and worst performers is still large, providing substantial room for continuing improvement.

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[11] More detailed information on IAEA activities concerning nuclear safety is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/) and at http://www-ns.iaea.org/.

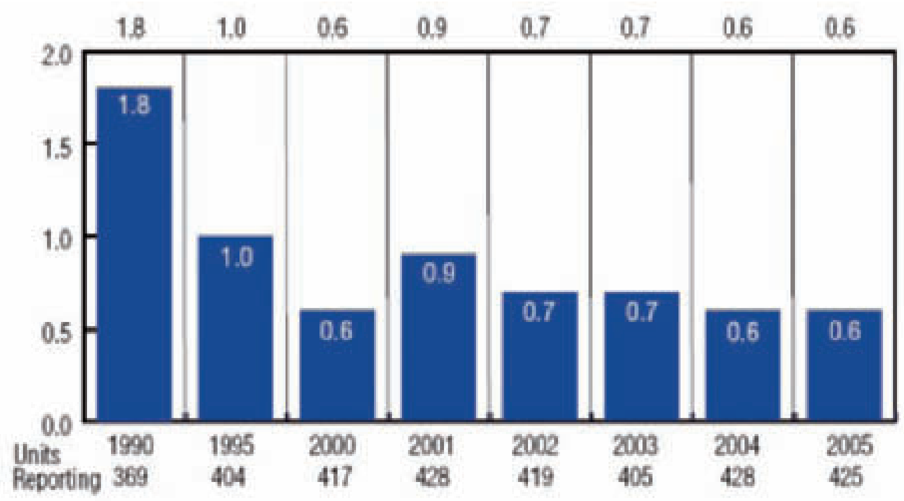

FIG. A-2. Unplanned scrams per 7000 hours critical. Source: WANO 2005 Performance Indicators.

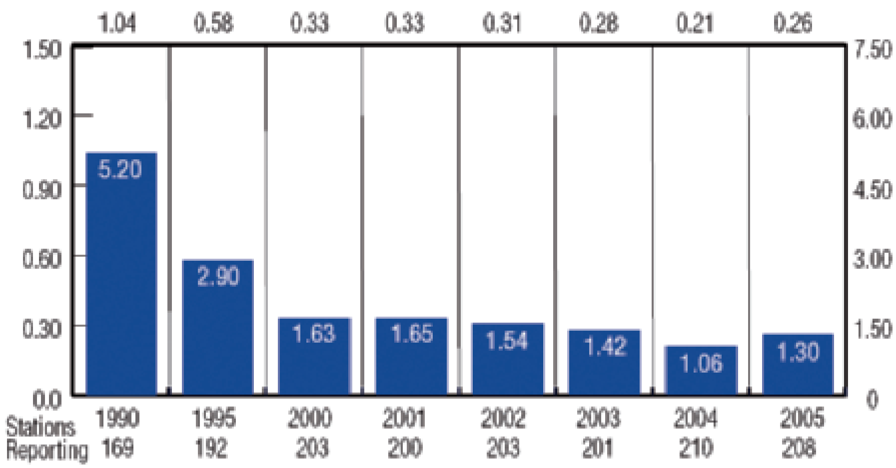

FIG. A-3. Industrial accidents at nuclear power plants per 200 000 person-hours worked (left scale) and per 1 000 000 person-hours worked (right scale). Source: WANO 2005 Performance Indicators.

More detailed safety information and recent developments related to all nuclear applications are presented in the IAEA's annual *Nuclear Safety Review* (GC/(51)/INF/2).

A.6.4. Proliferation Resistance[12]

At the 2005 NPT Review Conference, the Director General proposed seven steps to strengthen the non-proliferation regime: reaffirm the goal of eliminating nuclear weapons; strengthen the Agency's verification authority; establish better control over proliferation sensitive parts of the fuel cycle; secure and control nuclear material (e.g. strengthen the Convention on the Physical Protection of Nuclear Material and minimize high enriched uranium in civilian use); demonstrate a commitment to nuclear disarmament; strengthen the NPT non-compliance mechanism; and address the real security concerns of States. The issue of tighter control over proliferation-sensitive elements of the nuclear fuel cycle was discussed at the conference summarized in Section A.3 on 'New Framework for the Utilization of Nuclear Energy in the 21st Century: Assurances of Supply and Non-Proliferation'.

B. ADVANCED FISSION AND FUSION

B.1. Advanced Fission[13]

B.1.1. Light Water Reactors

In France and Germany, AREVA NP has developed the large European pressurized water reactor (EPR) to meet European utility requirements and benefit from economies of scale through a higher power level relative to the latest series of PWRs in France (the N4 series) and Germany (the Konvoi series). In Germany, AREVA NP, with international partners from Finland, France, the Netherlands and Switzerland is developing the basic design of the SWR-1000, an advanced BWR with passive safety features.

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[12] More detailed information on IAEA activities concerning proliferation resistance and safeguards is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/) and at http://www.iaea.org/OurWork/SV/Safeguards/index.html.

[13] Additional information is available in Annex IV. More detailed information on IAEA activities concerning advanced fission reactors is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2006/), and at http://www.iaea.org/OurWork/ST/NE/NENP/NPTDS.html.

In Japan, advanced boiling water reactor (ABWR) units benefit from standardization and construction in series. The first two ABWRs began commercial operation in 1996 and 1997, and two more began commercial operation in 2005 and 2006. Two ABWRs are under construction in Taiwan, China. A development programme was started in 1991 for ABWR-II with the goal of significantly reducing generation costs, partly through increased power and economies of scale. Commissioning of the first ABWR-II is foreseen for the late 2010s. Also in Japan, the basic design of a large advanced PWR has been completed for the Japan Atomic Power Company's Tsuruga-3 and -4 Units, and a larger version, the APWR+, is in the design stage.

In the Republic of Korea, benefits of standardization and construction in series are being realized with the Korean Standard Nuclear Plant (KSNP) series. Eight KSNPs are in commercial operation. The accumulated experience is the basis for developing an improved KSNP, the Optimized Power Reactor (OPR), with the first units planned for commercial operation in 2010 and 2011. The Korean Next Generation Reactor, for which development began in 1992, is now named the Advanced Power Reactor 1400 (APR-1400) and will be bigger to benefit from economies of scale. The first APR-1400 is scheduled to begin operation in 2012.

In the USA, designs for a large advanced PWR (the Combustion Engineering System 80+) and a large BWR (General Electric's ABWR) were certified in 1997. Westinghouse's AP-600 and AP-1000 designs with passive safety systems were certified in 1999 and 2006 respectively. An international team led by Westinghouse is developing the modular, integral 360 MW(e) International Reactor Innovative & Secure (IRIS) design with a core design capable of operating on a four-year fuel cycle. Design certification is targeted for 2008-2010. General Electric is designing a large European simplified boiling water reactor (ESBWR) combining economies of scale with modular passive safety systems. Both the IRIS and the ESBWR are currently subject to regulatory review.

In the Russian Federation, evolutionary versions of the current WWER-1000 (V-320) plants include the 1200 MW(e) AES-2000 design and WWER-1000 (V-392). The first WWER-1000 (V-392) was connected to the grid at Tianwan, China in 2006. Additional units are under construction in China, India and the Islamic Republic of Iran. Two units are planned at Russia's Novovoronezh site. Russia has also begun development of a larger WWER-1500 design. In July Russia and Kazakhstan created a joint venture to complete design development for a 200-400 MW(e) VBER-300 reactor for use in either floating or land-based co-generation plants.

The China National Nuclear Corporation (CNNC) has developed the AC-600 design, and is currently developing the CNP-1000 for electricity production. CNNC is also developing the QS-600e/w for electricity production and seawater desalination.

B.1.2. Heavy Water Reactors

In Canada, Atomic Energy of Canada Limited's (AECL's) advanced CANDU reactor (ACR) design uses slightly enriched uranium fuel to reduce the reactor core size, which reduces the amount of heavy water required to moderate the reactor and allows light water to be used as a coolant. Also, as a part of the Generation IV International Forum (GIF), AECL is developing an innovative heavy water moderated design with supercritical light-water coolant. Such reactors would also incorporate passive natural circulation heat removal wherever possible, and passive containment heat removal.

In 2005 and 2006 India connected the first two units using its new 540 MW(e) heavy water reactor (HWR) design at Tarapur. India is also designing an evolutionary 700 MW(e) HWR and is developing the Advanced Heavy Water Reactor (AHWR), a heavy water moderated, boiling light water cooled, vertical pressure tube type reactor which has passive safety systems, and is optimized to use thorium fuel.

B.1.3. Gas Cooled Reactors

Worldwide, there are currently 18 operating gas cooled reactors (GCR) cooled by carbon dioxide plus two test reactors cooled by helium. The South African Pebble Bed Modular Reactor company, PBMR (Pty) Ltd, is developing a 165 MW(e) pebble bed modular reactor (PBMR), which is expected to be commissioned around 2010. The South African Government has allocated initial funding for the project and orders for some lead components have already been made. In China, work continues on safety tests and design improvements for the 10 MW(th) high temperature gas cooled reactor (HTR-10), and plans are in place for the design and construction of a power reactor prototype (HTR-PM).

In Japan, a 30 MW(th) High Temperature Engineering Test Reactor (HTTR) began operation in 1998, and work continues on safety testing and coupling to a hydrogen production unit. A 300 MW(e) power reactor prototype is also under consideration.

The Russian Federation and the USA continue research and development on a 284 MW(e) gas turbine modular helium reactor (GT-MHR) for plutonium burning. France has an active R&D programme on both thermal as well as fast gas reactor concepts, and in the USA, efforts by the Department of Energy (DOE) continue on the qualification of advanced gas reactor fuel.

To demonstrate key technological aspects of gas cooled fast reactors, an experimental reactor in the 50 MW(th) range is planned for operation around 2017 in France.

B.1.4. Liquid Metal Fast Reactors

In China, the 25 MW(e) sodium cooled, pool type Chinese Experimental Fast Reactor is under construction, with first criticality foreseen for mid-2009 and grid connection in mid-2010. The next two stages of development will be a 600 MW(e) prototype fast reactor, for which design work started in 2005, and a 1000–1500 MW(e) demonstration fast reactor.

In France, the Phénix fast reactor will be operated for four additional irradiation cycles before being shut in 2009. It will perform irradiation tests in support of France's transmutation R&D programme and to support research on future innovative designs. Within the framework of the Generation IV International Forum (GIF), France plans to commission a 250–600 MW(e) prototype sodium cooled fast reactor around 2020 to demonstrate improved economics and enhanced safety characteristics.

In India, the Fast Breeder Test Reactor (FBTR) has been in operation since 1985, and the 500 MW(e) Prototype Fast Breeder Reactor (PFBR) is now under construction at Kalpakkam. It is scheduled for commissioning by September 2010.

In Japan, preparatory work began in 2005 on necessary modifications to the 280 MW(e) prototype fast breeder MONJU reactor prior to its restart. To develop advanced fuels and materials, and technology for minor actinide burning and transmutation, the JOYO reactor, an experimental fast breeder reactor, will begin irradiation of oxide dispersion strengthened ferritic steel, of uranium-plutonium MOX fuel containing 5% americium, and of MOX containing both neptunium and americium.

In the Republic of Korea, the Korea Atomic Energy Research Institute has conducted research, technology development and design work on the 600 MW(e) KALIMER-600 advanced fast reactor concept. The conceptual design was completed in 2006. From 2007 the development of sodium cooled fast reactor (SFR) technology will enter a new phase within the framework of the Generation IV SFR collaboration project.

The BN-600 in Russia is the world's largest operating fast reactor and has now been in operation for 26 years. The 800 MW(e) BN-800 is under construction with commissioning planned for 2012. Russia is also developing various concepts for advanced sodium cooled fast reactors and for heavy liquid metal cooled reactors, specifically the lead cooled BREST-OD-300 reactor concept and the lead-bismuth eutectic cooled SVBR-75/100 reactor concept.

In the USA within the framework of the Global Nuclear Energy Partnership (GNEP), initial R&D planning is underway for an Advanced Burner Test Reactor (ABTR) to demonstrate actinide transmutation in a fast spectrum as well as innovative technologies and design features important for subsequent commercial demonstration plants. Within the GIF framework, US activities are focused on gas cooled fast reactors (GFRs), lead cooled fast reactors (LFRs), and small modular sodium cooled fast reactors (SMFRs).

B.1.5. Accelerator Driven Systems (ADSs)

Particle accelerators combined with sub-critical nuclear reactors have the potential to produce less long-lived radioactive waste than other reactors and to transmute actinides and some long-lived fission products.

In China R&D activities focus on high power proton accelerator (HPPA) physics and technology, reactor physics of external source driven sub-critical cores, nuclear data and material studies. In Japan, the Japan Atomic Energy Agency (JAEA) has proposed a lead-bismuth eutectic cooled fast sub-critical core rated at 800 MW(th), and conceptual design studies for a Transmutation Experimental Facility (TEF) have begun. In the Republic of Korea, R&D on the Korea Atomic Energy Research Institute's (KAERI's) ADS system, HYPER (HYbrid Power Extraction Reactor), is in the third stage of a ten-year programme begun in 1997. It includes completion of the conceptual design of the HYPER core and the continuing investigation of key technologies.

In Europe, national R&D programmes in Belgium, France, Germany, Italy, Spain and Sweden are converging towards the demonstration of the basic aspects of the ADS concept. These include the EUROTRANS and EUROPART integrated projects within the framework programmes of the European Union. EUROTRANS is developing a preliminary design and supporting technologies for a European ADS demonstrator. EUROPART is developing the fuel cycle technologies to complement EUROTRANS system technologies.

In Russia recent ADS R&D highlights include the development and construction of the sub-critical assembly in Dubna (SAD) at the Joint Institute for Nuclear Research (JINR) and the substantiation of critical and sub-critical molten salt reactor concepts with a closed nuclear fuel cycle at the Russian Scientific Centre of the Kurchatov Institute in Moscow.

B.1.6. INPRO and GIF

The Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) grew to 28 members in 2006 with the addition of Belarus, Japan, Kazakhstan and Slovakia. INPRO provides an open international forum for studying nuclear power options and associated requirements. It helps to build up competence for developing and deploying innovative nuclear energy systems (INSs) and assists Member States in coordinating related collaborative projects. INPRO has developed a methodology, applicable to both developing and developed countries, to assess INSs in terms of economics, safety, environment, waste management, proliferation resistance, physical protection and infrastructure. Eleven assessments of INS are currently underway. Phase 2 activities began in 2006. They include further developing the INPRO methodology and user's manual based on feedback from current assessment studies, and identifying innovative institutional and infrastructure options to facilitate the deployment of INS including: consideration of regional approaches, harmonization of licensing processes and safety requirements, and new methods of financing with an emphasis on the needs of developing countries. Phase 2 will also coordinate collaborative projects including the identification of R&D needs. In particular INPRO will establish common user requirements for INS, with a focus on small and medium sized reactors, and determine, jointly with technology holders and users, the actions necessary for the development and deployment of such reactors.

The Generation IV International Forum (GIF) grew to 13 members in 2006 with the addition of China and Russia. Through a system of contracts and agreements, GIF coordinates research activities on the six next generation nuclear energy systems selected in 2002 and described in *A Technology Roadmap for the Generation IV Nuclear Energy Systems*: gas cooled fast reactors, lead alloy liquid metal cooled reactors, molten salt reactors, sodium liquid metal cooled reactors, supercritical water cooled reactors and very high temperature gas reactors. Four 'system arrangements' were signed in 2006 by interested GIF members, covering collaboration on sodium-cooled fast reactor systems, gas-cooled fast reactor systems, very high temperature gas-cooled reactor systems, and supercritical water-cooled reactor systems. The agreements provide the framework for GIF member countries to participate in collaborative research and development on various technologies.

B.2. Fusion

Research in controlled nuclear fusion is making steady progress with self-sustainable burning plasma as the next important major goal. Significant progress has been made in recent years towards this objective by using both laser power and radiation in the method called inertial confinement, or by using magnetic fields for confinement in what is popularly known as Tokamak systems, to confine and fuse light nuclei, deuterium and tritium. Large new facilities are currently under construction, the most prominent one using magnetic confinement being the International Thermonuclear Experimental Reactor, ITER. The partners in this unique international scientific endeavour to construct the world's largest fusion experimental facility represent more than half of the world population. The ITER parties signed two formal agreements on 21 November 2006 committing them to build the ITER in Cadarache, France: the Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project and the Agreement on the Privileges and Immunities of the ITER International Fusion Energy Organisation for the Joint Implementation of the ITER Project. The Director General of the IAEA serves as the Depositary of both agreements, which will go through the ratification process in national capitals over the next year. ITER, meaning 'the way' in Latin, is an important stage for the peaceful use of nuclear fusion and will drive most of the next generation magnetic confinement fusion research, building up the science and technology to construct a fusion power plant named 'DEMO'.

Inertial confinement is the main alternate approach and will be supported by several major facilities currently under design or construction, namely the National Ignition Facility (NIF) in the USA, the Laser Mega Joule (LMJ) in France and the Fast Ignition Realization Experiment programme in Japan.

There are still formidable technological challenges to be overcome in tapping fusion energy that are sufficiently demanding — scientifically, technologically, and in their resource requirements — that neither a single country nor a small group of countries can maintain the necessary research momentum over long periods. The IAEA provides a forum to help foster international cooperation, as demonstrated by the Fusion Energy Conference 2006, held in Chengdu, China, in October. More than 700 fusion scientists and engineers from 39 countries participated to exchange their latest developments and achievements.

Experimental fusion studies are heavily dependent on the ability to monitor and analyse the characteristics of the plasma (Fig. B-1). A new diagnostics database initiated by the IAEA represents a significant step in ensuring such studies are based on internationally accepted procedures and data. New cross-sections for a number of charge exchange processes have been measured and/or calculated to estimate the temperature and pressure of the plasma.

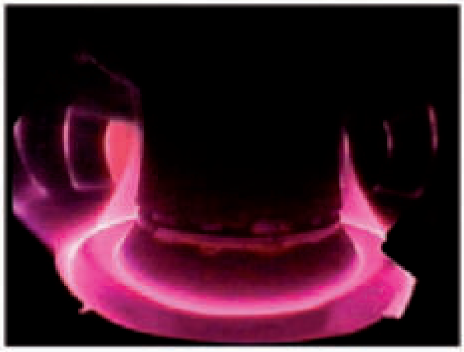

FIG. B-1. Fusion plasma diagnosis (glowing plasma in the ASDEX Upgrade tokamak, Germany).

C. ATOMIC AND NUCLEAR DATA

Increased demands for updated and more accurate atomic and nuclear databases, which are necessary to ensure sound and credible analyses of nuclear applications, including fission energy, are being made by more countries. The approval of ITER has created a similar increase in fusion research activities.

Much of the development work and the creation of good quality databases requires Agency encouragement. Significant international and national initiatives in recent years have included the assembly and release of JEFF-3.1 (Joint Evaluated Fission and Fusion) by the OECD/NEA in May 2005, and of ENDF/B-VII (Evaluated Nuclear Data File) by the USA in December 2006. Both databases contain recommended nuclear data that incorporate advances made through recent direct measurements; Agency data development projects; and modelling studies reflecting the improved understanding of a wide range of nuclear processes. Thus, continuing improvements are being made to the quality of various important neutron reaction cross-sections as a consequence of comprehensive measurements in the USA and Europe.

Developments in 2006 included the finalization of a high-quality neutron cross-section database for direct use in studies of the thorium–uranium fuel cycle; comprehensive re-evaluations of neutron cross-section standards; atomic and molecular data for fusion plasma diagnostics; and a database of cross-section data for the optimum production of therapeutic radionuclides in nuclear medicine. Important covariance data were produced to quantify the uncertainties of the thorium-232 and protactinium-231 and 232 cross-sections, and these data files have been rapidly adopted in national and international nuclear applications libraries. Similarly, a database of neutron cross-section standards has been adopted by the nuclear physics community. These data have been re-evaluated for a select set of reactions, and provide the foundation and reference for all subsequent nuclear data measurements and evaluations of these important nuclear parameters.

D. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

D.1. Accelerators

Materials science and biomedical research are driving developments in accelerators, novel analytical techniques, and improved nuclear instrumentation. In the low energy regime, compact and low-voltage machines are being developed and deployed for dedicated radiocarbon accelerator mass spectrometry applications. On the other end of the scale, synchrotron light sources are in increasing demand by large user communities. The following synchrotrons are currently being commissioned; Diamond in United Kingdom, Soleil in France, and Australian Synchrotron in Australia. SESAME in Jordan, Indus-2 in India, and Candle in Armenia are in the design or construction phase. There is wide demand for intense neutron beam sources for applications in biomedical and materials research, as well as radiation damage studies of potential material for use in extreme operating environments of advanced fission and fusion reactors.

D.2. Research Reactors

The main applications of most research reactors continue to be radioisotope production, neutron beam applications, silicon doping and material irradiation for nuclear energy systems, as well as teaching and training for human resources development. There is broad diversity in the features and capabilities of research reactors, and in their operation and utilization. Tables D-1 and D-2 and Figures D-1 and D-2 are based on the data available in the Agency's Research Reactor Database (RRDB).

TABLE D-1. Geographical Distribution of Research Reactors according to the Reactor Functional Status

	Operational	Shut down	Decommissioned	Under Construction	Planned	Total
Africa	9	1	0	1	1	12
America	66	127	73	2	1	269
Asia and Pacific	55	18	10	6	1	90
Europe	115	96	87	1	1	300
Total	245	242	170	10	4	671

TABLE D-2. Geographical Distribution of Operational Research Reactors according to the Reactor Power Level

	P = 100 kW	0.1 < P = 1 MW	1 < P = 10 MW	P > 10 MW	Total
Africa	2	2	2	3	9
America	30	19	13	4	66
Asia and Pacific	23	6	15	11	55
Europe	65	11	18	21	115
Total	120	38	48	39	245

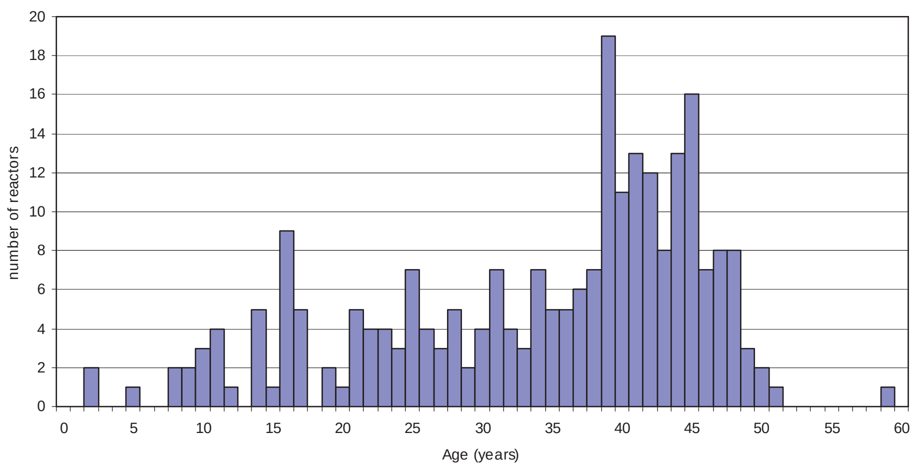

FIG. D-1. Age distribution of operational research reactors.

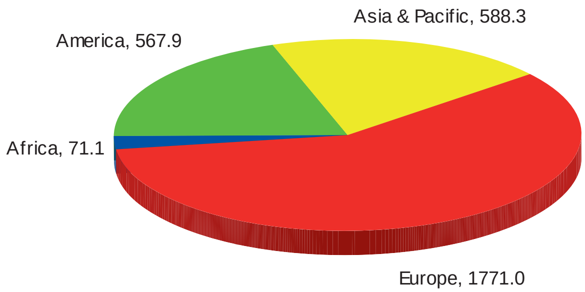

FIG. D-2. Installed power of operational research reactors in MW (Total = 2938.2 MW).

Among the new research reactors reported under construction in the *Nuclear Technology Review 2006*, the Open Pool Australian Light Water (OPAL) Reactor attained first criticality on 12 August 2006 and achieved its full operating power of 20 MW on 3 November 2006. The China Advanced Research Reactor (CARR) is scheduled to become operational by 2007 with radioisotope production, silicon doping and neutron beam applications as major activities. The TRIGA-II reactor in Morocco is in the commissioning phase.

The OPAL Reactor is a 20 MW pool type reactor using low enriched uranium (LEU) fuel (uranium silicide fuel) and cooled by water. It is a multi-purpose research reactor that will be used for radioisotope production, irradiation services and neutron beam research. Its compact core is designed to achieve high performance in the production of neutrons. Eight neutron beam instruments are planned at the OPAL Reactor. The facility can be expanded further and has the potential for a second neutron guide hall. A suite of equipment will enable studies at different temperatures, pressures and magnetic fields.

The above facilities are expected to be open to both the national and international user community on a time sharing basis, similar to those at Grenoble, France, and FRM-II, Germany.

With the revival of interest in nuclear energy, and with developments in fusion energy, the use of research reactors for materials studies continues to be of high interest, and research reactors will have an important role to play in the development of materials for advanced reactors. In addition, through regional collaboration and networking, more effective management, utilization and sharing of resources and expertise are evolving for research reactors, especially for neutron beam applications and radioisotope production for meeting regional needs.

The Reduced Enrichment for Research and Test Reactors (RERTR) Programme seeks to convert research reactors using high enriched uranium (HEU) fuel to LEU fuel. Forty-eight research reactors were converted to LEU fuel by the end of 2006, and around 50 others can be converted with available LEU fuel. However, for several specific research reactors, very high density U–Mo fuels are necessary to convert from HEU to LEU, especially for certain high-end operations. Development of such fuels is also useful to expand back end options for research reactor spent fuel management, as they will be amenable to reprocessing using currently available technologies and facilities. Continuing support for international coordination of the development and qualification of high density LEU fuels is essential in this regard. Initial irradiation testing of very high density U–Mo dispersions, beginning in the late 1990s, established the promising irradiation behaviour of these fuels. Subsequent experiments in different countries established shortcomings in fuel behaviour at high power and temperature. Detailed post-irradiation examinations indicate that fuel performance issues arise not from the poor performance of the U–Mo fuel particles, but from the swelling behaviour of the reaction layer that forms between the fuel and the aluminium matrix during irradiation. The demand for very high density, low-enrichment fuels requires a detailed programme of fuel fabrication development, out-of-pile characterization, irradiation testing, post-irradiation examination, and fuel performance evaluation and modelling. Several potential remedies are available to correct the known fuel performance problems: these range from relatively minor changes to the fuel and matrix chemistry, to replacement of the aluminium matrix with another material, or to elimination of the matrix altogether (monolithic fuel). All of these variations are currently being investigated collaboratively by Argentina, Canada, France, Germany, Republic of Korea, Russia and the USA. Recently reported post irradiation results from different experiments indicate that an addition of silicon in the order of 2% to 5% to the aluminium phase of dispersed U–Mo fuels effectively solves the problem of swelling at high power and temperature. Intensive research is going on towards developing very high density monolithic U–Mo fuel.

E. RADIOISOTOPE APPLICATIONS AND RADIATION TECHNOLOGY

E.1. Radioisotope Applications in Health[14]

Radioisotopes are contributing significantly to improving health care in most countries. Globally there is a growth in the number of medical procedures involving the use of isotopes, and with this a commensurate growth in the number of procedures requiring different isotopes, for example in diagnostic nuclear medicine and radionuclide therapy. Over 60 research reactors worldwide play a central role in the production of medical radioisotopes, with at least 11 reactors being built or projected to be built in a number of countries. As shown in a recent Agency survey[15], it is estimated that there are also about 350 cyclotrons available with many dedicated to the production of positron emission tomography (PET) isotopes.

The most significant increase in the requirement of isotopes recently has been for the cyclotron produced fluorine-18, as fluorodeoxy glucose (FDG/^{18}FDG), for PET applications in the detection, staging and treatment follow up of various types of cancers, and for the reactor-produced lutetium-177 for radionuclide therapy, for use, for example as labelled peptides for the treatment of neuroendocrine tumors or as labelled phosphonates for bone pain palliation. In addition there is a large demand for yttrium-90 for radionuclide therapy and consequently there is increasing interest in the isolation and purification of the parent radionuclide strontium-90 from spent fuel. With the growth in PET units in medical centres, interest in positron emitting radionuclides that are available from radioisotope generators, especially germanium-68/gallium-68, is also increasing. The availability of such generators not only helps in conducting PET studies in centres which do not have cyclotrons, but also enhances the quality of information from PET imaging of tumours with gallium-68 products. Interest in radioisotopes of copper has been on the increase due to the merits of using copper-64/copper-62 for PET imaging and dosimetry.

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[14] Additional information is available in Annex II.

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, *Directory of Cyclotrons used for Radionuclide Production in Member States,* IAEA-DCRP/CD, IAEA, Vienna (2006).

E.2. Radiation Technology

In 2006, three major international meetings, namely the International Meeting on Radiation Processing (IMRP-2006), the 11th Tihany Symposium on Radiation Chemistry, and the 7th International Symposium on Ionizing Radiation and Polymers (IRaP-2006), were held covering both fundamental and applied aspects of radiation technology, among which the radiation grafting of polymers was extensively elaborated. Radiation provides a highly advantageous means of grafting, defined as the ability to attach or grow a different material onto the backbone of another.

E.2.1. Radiation Grafting of Polymers

The current trends in research and development studies show that, at present, radiation grafting on polymers is developing in three main directions, namely for adsorbents, membranes, and for use in medicine and biotechnology. With polymeric materials, the 'different' material is most typically a monomer and the 'backbone' is a polymer or another solid. A chemical bond is formed between the grafted half and the material. Figure E-1 is an example from Japan

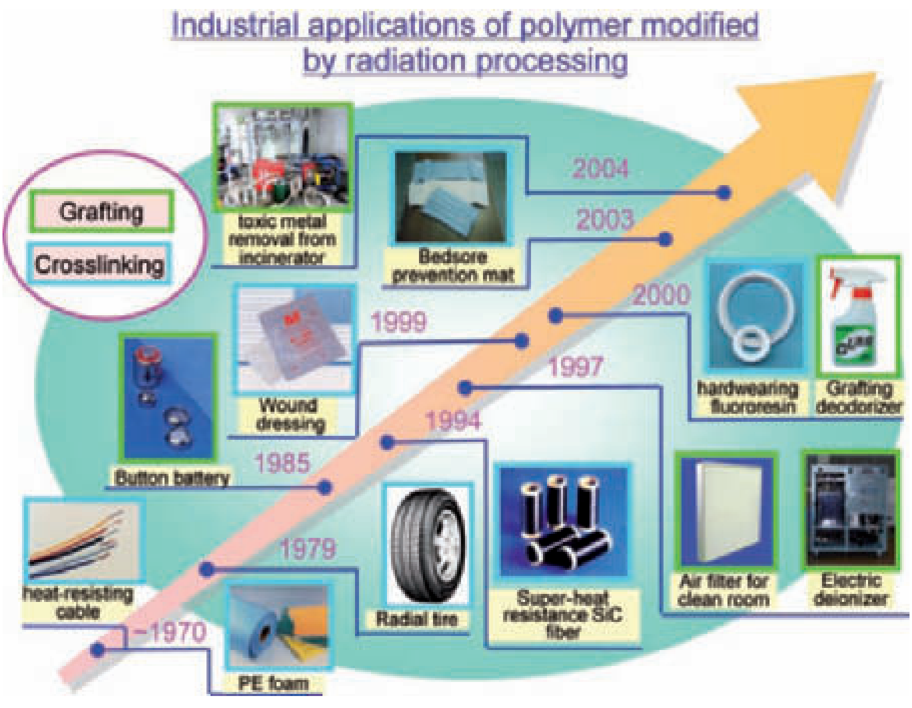

FIG. E-1. Evolution in industrial applications of radiation processing.

of the evolution in industrial applications of radiation processing, including grafting of polymers.

Polymeric adsorbents

Graft polymerization has been industrially applied in the production technology for adsorbents of metal ions and malodorous gases. Research and development into the synthesis of metal ion adsorbents by using pre-irradiation grafting techniques has resulted in adsorbents which could be applied for the removal of toxic metal ions such as arsenic, lead and cadmium, and the recovery of metals such as uranium and scandium.

Polymeric membranes

Fuel cells are a promising source of power for stationary and portable applications. Fuel cell performance depends largely on the membrane at the heart of the cell, which has to be stable in the hostile environment of hydrogen and oxygen at elevated temperatures. The membrane acts as a separator to prevent mixing of the reactant gases and also as an electrolyte for transporting protons from the anode to the cathode. Currently one of the most promising ways in which to obtain low cost proton-conducting polymer electrolyte membranes is to use radiation grafting techniques. The method allows the use of a wide variety of base films and monomers which may be tailored for specific applications. Membranes fabricated by radiation grafting offer a cost competitive option, since inexpensive commercially available materials are used.

Polymers for medicine and biotechnology

The possibility of re-creating various tissues and organs with advanced technology has received much interest for the purpose of regenerative medicine. A method known as ‘cell sheet engineering’ utilizes temperature-responsive culture surfaces, which are created by radiation-induced grafting of temperature-responsive polymers by electron beam irradiation. The grafted polymer thickness and density are precisely regulated in a nanometre regime. These surfaces allow for the non-invasive harvest of cells by simple temperature regulation. The harvested cell sheets have been used for various tissue reconstructions, including ocular surfaces, periodontal ligaments, cardiac patches, oesophagus and various other tissues.

F. NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

F.1. Isotopes in Soil for Tracking Pollutants

Isotopic and nuclear techniques play an important role in identifying the source of pollutants from different land use practices and farming activities[16]. If the specific sources of pollutants are unknown, environmental planners, farmers or policy makers face a difficult task in deciding upon the most appropriate management strategy to reduce pollutants' impacts. For example, fertilizers and farmyard manure that are applied to enhance crop growth and pesticides used for disease control in crops and livestock can become pollutants if they find their way into streams, lakes and rivers. In these aquatic environments they become toxic to fish, create excessive weed growth in the waterways and potentially affect recreational activities causing subsequent economic loss to the tourism industry. Both stable isotopes and fallout radionuclides in soil, water or sediment samples can help to accurately pinpoint the sources of these agricultural pollutants from catchments. Fallout radionuclides such as caesium-137, lead-210 and beryllium-7 are airborne radioactive debris originating from man-made activities such as nuclear weapon testing and other sources, primarily the Chernobyl accident, as well as from the natural collision of cosmic rays. These fallout radionuclides are attached to soil particles and can therefore be used as fingerprints to track the movement of soil particles from where they originate in an agricultural catchment to waterways. In addition, fertilizers, farmyard manure, pesticides and animal excreta deposited by grazing animals in an agricultural catchment carry distinct stable isotopic signatures (e.g. carbon-13 and nitrogen-15). Thus specific areas within a catchment may have distinctly different stable isotopic signatures (natural biomarkers) because of varying agricultural uses and animal grazing patterns. These different signatures offer a 'forensic tool' in environmental soil science to verify the origin of a range of pollutants such as nitrate, phosphate, and pesticides in waterways.

Soil studies using stable isotopic signatures also assist in the understanding of climate change. Isotopes such as carbon-13 and nitogen-15 can be used as fingerprints to investigate how soil acts as a sink for greenhouse gases. Changes in soil carbon and nitrogen isotopes are expected to reflect the shift in soil organic matter as influenced by variations in the levels of greenhouse gases in the atmosphere and land use activities.

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[16] Additional information is available in Annex I.

F.2. Crop Improvement

Mutation induction plays a major role in the development of new and improved crop varieties. In the last decade research in mutation induction in crop improvement has intensified, and further extended to include identifying and understanding the role of specific genes.

The technology is being used to develop crop varieties with improved nutritional quality, including reduction of anti-nutritional agents. The genetic changes resulting from induced mutations alter the expression of genes affecting various biochemical pathways. Calcium oxalate (a compound that forms needle-shaped crystals, and found in varieties of poisonous plants) for example, is not a nutrient or a beneficial source of calcium, and can be toxic in large doses. It is found in many leafy and nutritious vegetables, including spinach, Swiss chard and other edible vegetables. Minimizing oxalate through mutation induction has the potential to make vegetables more nutritious and digestible.

The mutagenic effect of cosmic rays and their role in natural mutations and evolution is being investigated. Since the first international experiments in the 1970s on the Apollo 16 mission, which investigated the effects of cosmic rays on different organisms, a 'space breeding programme' was initiated at the Chinese Academy of Agricultural Sciences, which has resulted in a spectrum of new crop mutants including super yielding rice varieties, resistance to rice blast fungal diseases, and vegetables such as tomato and pepper with giant fruit size.

Radiation hybrid mapping is a technique based on exposing somatic cells to lethal doses of γ radiation or X-rays, in order to fragment the chromosomes. These are then rescued by introducing them into microcells which are subsequently fused with suitable recipient cells. The technique was developed to facilitate the sequencing of the human genome and this methodology, which allows whole genomes to be mapped, has now been transferred to plant systems. Radiation hybrid maps for a number of crops such as barley, maize, wheat and cotton have been developed for detailed analyses and sequencing of their genomes, which will facilitate the identification and transfer of genes affecting useful agronomic, quality and stress tolerance traits to improve crops.

F.3. Improving Livestock Productivity and Health

In the quest for more and better livestock and livestock products, molecular and nuclear related technologies have played and will continue to play an important role. Uses include the identification, manipulation, and characterization and tracing of proteins, DNA and RNA. Developments in detection technologies, such as phosphor-imaging, micro-fluidics to enable sample-to-result to be done in one step, and use of nanotechnologies, offer possibilities for the introduction and use of more sensitive, rapid and robust devices under both laboratory and field conditions.

Stable isotopes are increasingly used in animal production and health applications. Carbon-13 or nitrogen-15 labelled feeds, or adding carbon-13 or nitrogen-15 labelled compounds directly to the rumen (the first stomach of the ruminant animal), provide good insights into the metabolism of carbohydrate and protein and nutrient uptake. The ruminant manure produced could also be used for mapping the fate of carbon and nitrogen in soil and plants. Such information helps develop strategies for optimum feed utilization and helps to make the overall production system more efficient and sustainable. Comparisons of stable isotopic signatures in animal body fluids or products with those of the potential feeds enable diet selection and changes to be recorded and can be used to differentiate intake of tropical grasses and other feedstuff. The same type of information can also be utilized to determine the origin of animal products non-invasively. This approach has potential in determining the possible roles that wild animals play as carriers of animal diseases, a case in point being the contribution from migratory birds towards the spread of avian flu from endemic to uninfected areas. A stable isotope-labelled water (deuterium oxide) dilution technique is being increasingly used for the determination of lean body mass, fat content, body composition, and total body water and milk intake by calves. Conventionally, the deuterium oxide concentration in body fluid has been measured by isotope ratio mass spectrometry, but recent studies have shown that a relatively inexpensive technique, infrared spectroscopy can also be used with the same accuracy.

F.4. The Sterile Insect Technique for Insect Pest Control

All area-wide insect pest control programmes releasing sterile insects currently use radio-isotope irradiators for sterilization, which is a proven and reliable technology. However, the re-loading of existing radiation sources and the acquisition and international shipment of new sources is presenting problems, with at least one major producer leaving the market altogether. An alternative technology using X-ray irradiation is under development, and a new screwworm facility in Panama will use exclusively X-rays for sterilization. It is likely in the future that there will be a large increase in the development and use of X-ray machines for the sterile insect technique (SIT) and related programmes.

F.4.1. SIT against Fruit Flies

The use of SIT as a component of area-wide integrated pest management programmes for the control of major agricultural pests continues to expand and in 2006 several new facilities began operations. In Juazeiro, State of Bahia, Brazil, a Mediterranean fruit fly mass rearing facility was inaugurated in September 2006, dedicated initially to the weekly production of about 100 million sterile males. The development of the facility has been supported, inter alia, by the Agency's technical cooperation programme, and will service the rapidly expanding commercial fruit (mango, grapes, etc.) production areas of the various irrigation districts around the San Francisco River in the arid northeast of Brazil. Future expansions of the facility foresee also the production of some *Anastrepha* spp. fruit flies, as well as fruit fly parasitoid mass rearing. The potential of the project to reduce insecticide applications by suppressing fruit flies in an environment-friendly way is large. The ultimate goal is to eliminate the costly post-harvest treatments by establishing low prevalence and fruit fly free areas officially recognized by trading partners.

In Spain, in the major citrus-producing region of Valencia, another Mediterranean fruit fly rearing and sterilization facility has been constructed which will produce 400 million sterile males per week. Technical support has been provided under a memorandum of understanding between the Joint FAO/IAEA Programme on Nuclear Techniques in Food and Agriculture and the Agriculture, Fishing and Food Department of the Valencian Government.

The entire Patagonia region in Argentina is now officially recognized as the first fruit fly free area in the country by the Animal and Plant Health Inspection Service (APHIS) of the United States of America (Fig. F-1.). This

FIG. F-1. Apple and pear production areas in Patagonia.

major success is the culmination of ten years of joint efforts of the federal and provincial governments and the fruit industry. Technical support to this effort from national and international organizations, including the National Institute for Agricultural Technology (INTA), FAO and the Agency, contributed to this success. This achievement will allow Patagonia to export fresh fruits and vegetables to the USA without any quarantine treatments, which according the National Food Safety and Quality Service (SENASA) represents annual savings of two million dollars. Following these successes, the Secretariat of Agriculture, Livestock, Fisheries and Food has now announced its approval to fund the initiation of a new fruit fly management programme also involving SIT implementation over an area of 56 000 hectares comprising the main citrus producing provinces of Argentina (Entre Ríos and Corrientes) in the northeast of the country.

F.4.2. SIT against the Screwworm

In Panama a new facility for rearing about 100 million New World screwworm flies was inaugurated in July 2006. During the past three decades, the successes of the screwworm eradication programme relied on the mass rearing facility of the Mexico–American Screwworm Eradication Commission based in Tuxtla Gutiérrez, Chiapas, Mexico, which has provided the sterile flies for all eradication campaigns in Mexico, Central America and the Caribbean. In recent years its much reduced production has also been providing sterile flies to maintain the sterile fly barrier in eastern Panama and to the ongoing eradication programme in Jamaica.

F.4.3. SIT against Mosquitoes

There is interest in applying the SIT not only against the malaria transmitting *Anopheles* mosquitoes, but also against those mosquitoes that transmit important virus diseases such as dengue and Chikungunya. In Rimini, Italy, an experimental pilot SIT project has been initiated to control the mosquito *Aedes albopictus*, the vector of dengue. Methods have been developed to produce large numbers of male pupae for sterilization and release. Significant sterile male releases have been made in an area in Rimini resulting in measurable effects on the population density of the vector. The same species of mosquito has also been the cause of a recent major epidemic of chikugunya fever on islands in the Indian Ocean, especially Reunion.

F.5. Food Quality and Safety

F.5.1. Safety Monitoring: Measuring Pesticide Residues

Validated analytical methods are essential for implementing food safety monitoring programmes. The performance and applicability of such methods in laboratories in developing countries needs to be optimized. In addition, it is a requirement of the relevant laboratory quality assurance protocols that results are reported with an estimate of their associated uncertainty. The Agrochemicals Unit of the Agency's Laboratories at Seibersdorf have assisted in developing such protocols for the use of radiolabelled compounds to optimize sample preparation, extraction, clean-up and analytical steps during the development of chromatographic analytical methods to be used in regulatory programmes for analysis of residues of pesticides and other contaminants in food and environmental samples. The protocols also assist in the estimation of the measurement uncertainty associated with the methods.

G. HUMAN HEALTH

G.1. Advances in Nuclear Cardiology

Innovative strategies in nuclear techniques have propelled the field of nuclear cardiology from the assessment of coronary blood flow to the heart muscle and its ability to pump blood into the main arteries into molecular imaging. Combining information provided by positron emission tomography (PET) and by modern computed tomography (CT) scanners in hybrid PET–CT systems now allows the assessment of coronary artery disease at its very early stages. The added value of this technology is particularly important in patients having conditions such as diabetes, hypertension and elevated levels of blood lipids. This intricate structural and molecular information at the cellular level allows individual risk assessment of future severe and possibly deadly myocardial events. Individual risk assessment makes it possible to provide advice on life-style changes, or early medical intervention, with a view to retarding the course of the cardiovascular disease and diminishing the associated risk factors.

From the clinical point of view, the choice of the most appropriate diagnostic modality at different stages of the cardiovascular disease will depend on the nature of the clinical setting and the specific question being asked. With an increased emphasis on prevention and a concomitant ageing of the population in developed and in developing Member States, non-invasive cardiac imaging will continue to grow and to impact the management of patients with cardiovascular disease worldwide.

G.2. State-of-the-art of Radiotherapy

In radiotherapy, the identification and delineation of tumours made possible by PET/CT and magnetic resonance imaging (MRI) allows planning radiotherapy treatments to take into account both the anatomical features seen on CT as well as the molecular imaging produced by PET and MRI technologies.

The use of new techniques for delivering radiotherapy is gaining popularity. Three-dimensional conformal radiotherapy (3D-CRT) includes virtual or CT simulation techniques and 3D treatment planning. It aims to shape the dose distribution produced by radiation beams more closely to the tumour volume, by focusing the beams in three dimensions. Intensity-modulated radiation therapy (IMRT) has evolved from 3D-CRT. The dose distribution plan is first specified by the physician, as in conventional radiotherapy, but highly sophisticated computer algorithms then work out the optimized configuration of beam directions and intensities within each of the beams in order to achieve the prescribed dose–volume distribution. It is performed with a linear accelerator (linac) equipped with a multileaf collimator (MLC). A machine called the Cyber-Knife uses robotically driven movements enabling more precision of the highly-focused radiation beams. IMRT can be used to produce dose distributions that are far more conformal than those possible with standard 3D-CRT. This in turn means that the volume of normal tissue exposed to high doses can be reduced significantly. However, although tailoring dose distributions with high accuracy has significantly mitigated the adverse effects of radiation treatment (morbidity), it still remains to be seen whether more cancer patients are cured or their lives extended longer than with simpler technologies.

Rapid developments are also occurring in methods to overcome the problem of tumour and body organ motion. Body parts move, both during radiation treatment sessions and from one treatment session to another, owing to respiration, digestion, and small differences in the way the patient is positioned for each treatment. This motion can result in an excessive dose being applied to normal tissues surrounding the tumour, and inadequate treatment of the tumour itself. Image guided radiotherapy (IGRT) involves imaging the patient lying in the treatment position on the couch, immediately

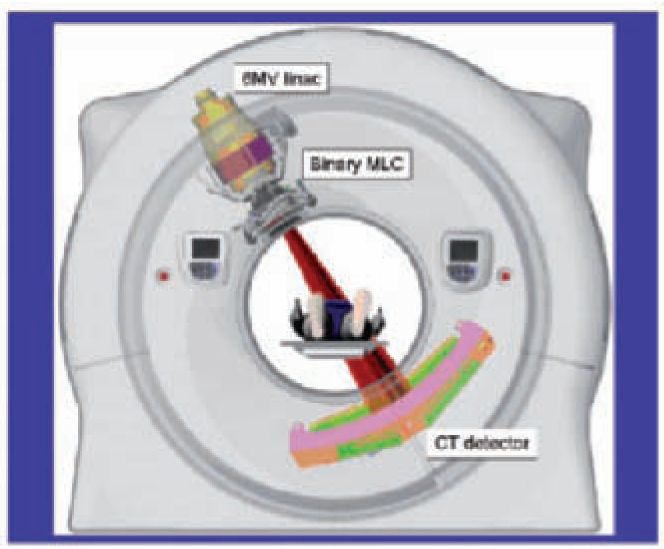

FIG. G-1. Combined tomography–therapy treatment.

before the treatment and during treatment sessions. It is used to identify shifts in tumour and organ location and to track movement, which makes it possible to modify the radiotherapy treatment to the current position. In conjunction with a respiratory ‘gating’ system that switches the treatment beam on and off in synchrony with respiratory motion, it is possible to restrict treatment to the portion of the respiratory cycle when the tumour is in line with the beam, thus increasing dose to the tumour and reducing the dose to surrounding tissues. In a combined tomography–therapy machine (see Fig. G-1), a linac replaces the X-ray tube and treatment is delivered while the linac rotates around the patient and radiation dose is modulated using a binary multileaf collimator (MLC). A detector registers the linac radiation coming through the patient and images of very high quality are made at the same time as the treatment is performed. Owing to the degree of sophistication achieved, this process and IGRT in general has been termed adaptive radiotherapy (ART).

G.3. Nutrition

The urgent need for effective nutritional interventions is clearly indicated by the current global situation where, on the one hand, 170 million children are underweight and undernutrition is an important factor in more than half of all child deaths worldwide and, on the other hand, more than a billion adults are overweight. This phenomenon is known as ‘the double burden of malnutrition’.

It results in a heavy burden on health systems in countries where treatment of diet-related diseases, such as heart disease and diabetes, will be increasingly needed at the same time as undernutrition and communicable diseases are still prevalent.

The use of nuclear techniques, in particular in the use of stable isotope techniques, can assist in the development and evaluation of nutritional interventions. In particular, the Agency's activities in human nutrition are focusing on the importance of preventing and treating malnutrition during the 'window of opportunity', i.e. during pregnancy and the first two years of life.

The wider application of these techniques related to nutrition programmes in developing countries is an example of recent developments in applied nutrition. Increased access to analytical equipment, such as isotope ratio mass spectrometers (IRMSs) dedicated to nutrition projects, will contribute significantly to an increase in the application of stable isotope techniques in the near future. Of particular interest is the recent development of less expensive equipment such as Fourier transform infrared (FTIR) spectrometer for analysis of deuterium (a stable isotope of hydrogen) to assess body composition and to measure the intake of human milk in breastfed infants.

H. WATER AND THE ENVIRONMENT

H.1. Isotopic Data for Water Resource Management

The occurrence and distribution of water resources, both in surface water bodies and in aquifers, is determined to a large extent by the prevailing climate regime. Improved understanding of the water cycle and the potential impact of climate change has been recognized as a key element of sustainable water resources management efforts. Isotope contents in precipitation, rivers and groundwater — particularly stable oxygen and hydrogen isotopes and tritium — help to understand the relationship between the water cycle and climate. Isotope data, therefore, are extremely useful in unraveling the impacts of climate variability on water resources. Present worldwide research on the rates of glacial accumulation and disappearance rely heavily on isotope analysis of ice cores and their relationship to the isotopes in present precipitation. Other aspects of isotope applications for water resource management also depend on the isotope composition of modern precipitation.

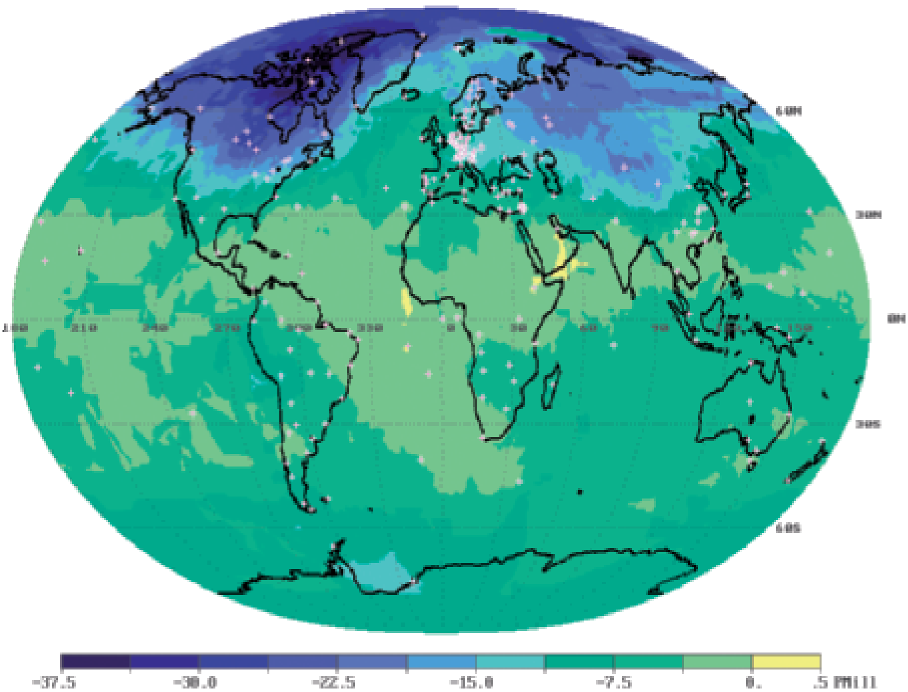

FIG. H-1. The temperature dependence of isotopes: oxygen isotopes in January.

Recognizing this important application of isotope data, a number of countries are taking steps to broaden the availability of isotope data at a national scale. During 2006, a project was initiated in India to focus on the collection and interpretation of isotopic compositions of precipitation, river flow and groundwater. Thailand has also initiated similar efforts towards setting up a national database.

These national efforts will further strengthen the Global Network for Isotopes in Precipitation (GNIP) that has been operated by the IAEA since 1961. Distribution of oxygen isotopes in precipitation, as measured in a typical cold month of January in the northern hemisphere, is presented in Fig. H-1 which shows the strong temperature dependence of isotopes (colder areas have lower isotope ratios). Isotope data from GNIP provide countries with a tool for meaningfully interpreting and using their national or local isotope data. In addition to helping to understand climate impacts on the water cycle, GNIP data are critical for such diverse applications as the assessment and management of groundwater resources, identification of sources of pollution, and authentication of the origin of fruits and vegetables.

H.2. Marine and Terrestrial Environments

H.2.1. Microanalysis of Radioactive Particles in Marine Sediments

A major fraction of both natural and human-made radionuclides entering the marine environment is associated with particles of biological, mineral or nuclear origin. It is known, for example, that naturally occurring radioisotopes of polonium, thorium and lead in the ocean are scavenged by sedimenting marine particles on their journey to the deep ocean[17]. Some anthropogenic radionuclides found in the marine sediments occur in microscopic 'hot particles'. Such particles represent point sources of possible radiological significance if ingested by marine organisms or people, and long-term assessment of hot particles in the oceans, their properties and biogeochemical behaviour needs to be determined. A range of micro-imaging and analytical techniques is now available, including scanning electron microscopy, synchrotron-based micro X-ray techniques and micro mass spectrometric techniques, such as secondary ion mass spectrometry (SIMS) and inductively coupled plasma mass spectrometry (ICP-MS).

H.2.2. Radiotracers in Support of Seafood Safety

Marine aquaculture of bivalve molluscs (e.g. mussels, oysters and scallops) is a globally and economically growing activity, which, however is constantly at risk because of the sensitivity of these seafoods to bioaccumulate toxic metals to levels exceeding seafood safety and export guidelines.

The use of radiotracer techniques offers cost-effective diagnosis for management strategies to mitigate these risks. Radiotracers enable sensitive tracking of the uptake, localization and elimination of toxic metals in both target organisms (bivalves, fish, shrimp) and through whole marine food chains. For example, it is now known that scallops bioconcentrate large amounts of the toxic metal cadmium in their tissues to levels which are often higher than internationally recommended guidelines. Studies using a cadmium-109 radiotracer with autoradiography have demonstrated that the cadmium becomes concentrated almost exclusively in the kidney and in the digestive gland (see Fig. H-2), which are not generally eaten by consumers and therefore can be removed before entering the food chain. These radiotracer studies thus provide the

[17] Additional information is available in Annex III.

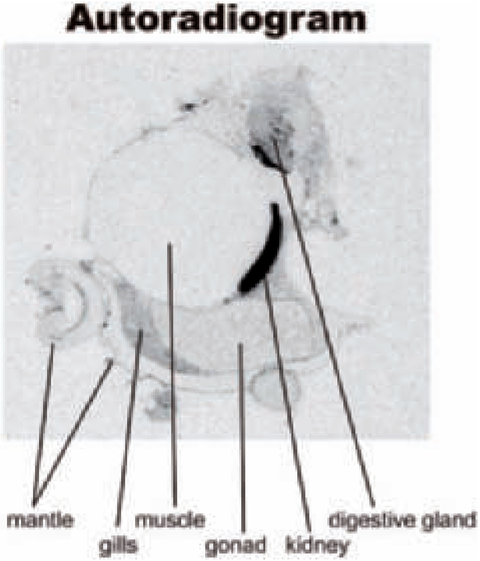

FIG. H-2. The black areas indicate the concentrations of the radiotracer cadmium-109 in a scallop (Credit C. Rouleau, IML, Canada).

shellfish industry with practical measures to improve the quality of seafood for international markets.

H.3. Air Pollution Monitoring

Air pollution caused by suspended particulate matter is a threat to human health, especially in larger cities. Fine pollution particles can penetrate deeply into the lungs and may remain there for a substantial time. Effective air quality management regimes mean that that the sources of particles causing the air pollution are known. Nuclear analytical techniques (X-ray fluorescence, neutron activation analysis and ion beam techniques) are tools that can be used for determining the elemental composition of air particulate matter. When this is known, the particular source may be identified, or the relative contributions of different types of pollution sources can be assessed, for example, identifying pollution from vehicles, industries, or from transboundary sources. Based on such information decisions can be taken on actions to reduce emissions, for example by reducing or banning leaded petrol, or improving urban transport infrastructure. Particular success in such measures has been seen in South-East Asia. Nuclear analytical techniques can similarly be used to measure the effectiveness of pollution countermeasures.

FIG. H-3. A high volume air sampler, for use in air pollution or radon monitoring.

H.4. Radon in the Atmosphere

Radon is a natural radioactive gas which is continuously entering the atmosphere from the earth's surface. The half-life of radon-222 (3.82 days) is comparable with the lifetimes of many atmospheric pollutants such as sulphur dioxide, nitrous oxides and ozone. Consequently, radon measurements are increasingly being used in studies of atmospheric processes, in particular for testing atmospheric circulation and transport models.

Radon concentrations vary with wind direction, especially near the coast as radon flow into the atmosphere is much lower from the ocean than from soils. This means that radon can be used as an indicator of the degree of contact of the air mass with land. An example of this application is the incorporation of radon measurements as a part of the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO). GAW aims to make reliable observations of the chemical composition and selected physical characteristics of the atmosphere on global and regional scales; provide the scientific community with the means to predict future atmospheric states and organize assessments in support of formulating environmental policy. These requirements of atmospheric studies are currently driving improvements in radon detection systems in several areas.

H.5. Reference Materials and Analytical Quality

Environmental monitoring requires increasingly accurate measurements and repeatable results for, inter alia, sustaining confidence in food security and

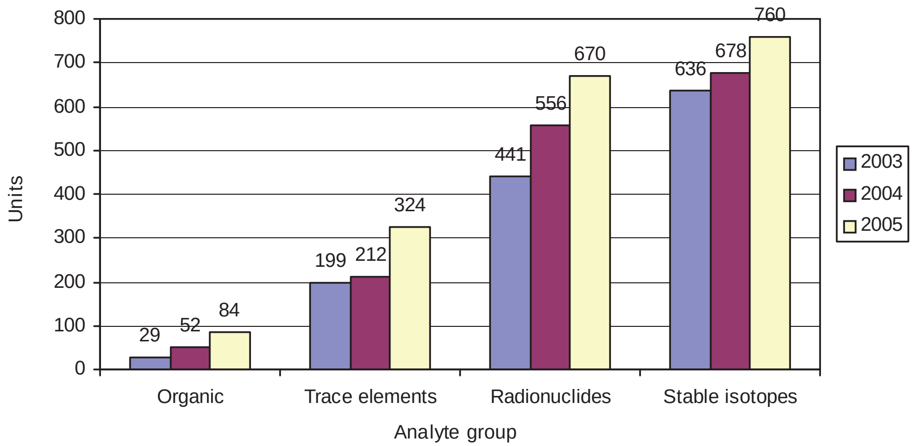

FIG. H-4. IAEA reference materials units distributed in 2003, 2004 and 2005.

international trade. Laboratories worldwide are strengthening the provision of tools for assuring comparability and quality of measurement results in two main directions. The first is an appropriate measurement infrastructure, which primarily involves national metrology institutes and the provision of necessary calibration standards. The second is the availability of quality assurance and quality control tools, which includes reference materials. These are similar to common sample types, and contain known amounts of substances routinely analysed. The number of types of materials and analysed substances in environmental monitoring and studies is large and the demand by laboratories for appropriate reference materials is very high.

Nuclear technology and reference materials are strongly related from two sides. Firstly, nuclear and related analytical techniques (such as neutron activation) are considered as reference techniques for the characterization of new reference materials. Secondly, reference materials are applied routinely to check the quality of measurement results obtained by nuclear analytical techniques. The need for high quality and metrologically well-established reference materials characterized for radionuclides, stable isotopes, trace elements, organic pollutants, etc. is continuously growing (see Fig. H-4). To ensure proper confidence in measurement results, international bodies such as the International Organization for Standardization (ISO) and Co-operation on International Traceability in Analytical Chemistry (CITAC) are giving more attention to the area of reference materials production.

Annex I
WATER USE EFFICIENCY IN AGRICULTURE: THE ROLE OF NUCLEAR AND ISOTOPIC TECHNIQUES

A. Introduction

Agriculture is the predominant user (75–80%) of the available freshwater resource in many parts of the world. At present most of the water used to grow crops is derived from rainfed soil moisture, with non-irrigated agriculture accounting for some 60% of production in developing countries. Although irrigation provides only 10% of agricultural water use and covers just around 20% of the cropland, it can vastly increase crop yields, improve food security and contribute 40% of total food production since the productivity of irrigated land is three times higher than that of rainfed land. The Food and Agriculture Organization (FAO) predicts a net expansion of irrigated land of some 45 million hectares in 93 developing countries (for a total of 242 million hectares in 2030) and project that agricultural water withdrawals will increase by approximately 14% during 2000–2030 to meet food demand[18].

Competition among different sectors for scarce water resources and increasing public concern on water quality for human, animal and industrial consumption and recreational activities have focused more attention on water management in agriculture. As water resources shrink and competition from other sectors grows, agriculture faces a dual challenge: to produce more food with less water and to prevent the deterioration of water quality through contamination with soil runoff, nutrients and agrochemicals.

Current response measures, including policies and regulations, consist of a combination of ways to ensure adequate and more equitable allocation of water for different sectors. Measures include improving water use efficiency, pricing policies and privatization. Similarly, there is an emphasis on integrated water resources management, which takes into account all the potential stakeholders in the planning, development and management.

B. Improving Water Use Efficiency in the Agricultural Sector

Water use efficiency (WUE) is a broad concept that can be defined in many ways. For farmers and land managers, WUE is the yield of harvested crop

[18] http://www.fao.org/newsroom/en/focus/2006/1000252/index.html.

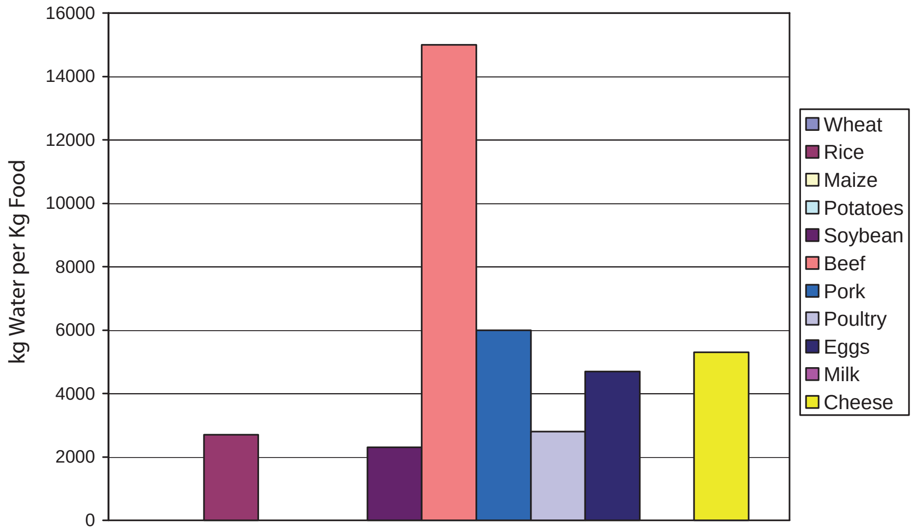

FIG. I-1. Water needed for food production (litres of water per kilo of food).

product achieved from the water available to the crop through rainfall, irrigation and the contribution of soil water storage.

Improving WUE in agriculture will require an increase in crop water productivity (an increase in marketable crop yield per unit of water removed by plant) and a reduction in water losses from the plant rooting zone, a critical zone where adequate storage of moisture and nutrients are required for optimizing crop production. The amount of water required for food production depends on the agricultural commodities produced (see Fig. I-1). For example, the production of 1 kg of beef would require 14 times more water than for 1 kg of wheat. Thus improving WUE in agriculture may also require some socio-economic adjustment to encourage more water efficient enterprises.

Improving WUE by 40% on rainfed and irrigated lands would be needed to counterbalance the need for additional withdrawals for irrigation over the next 25 years from additional demand for food. However, this is a big challenge for many countries.

Increasing WUE is a paramount objective, particularly in arid and semi-arid areas with erratic rainfall patterns. Under rainfed conditions, soil water can be lost from the soil surface through evaporation (termed **soil evaporation**) or through plant uptake and subsequently lost via openings on plant leaves (termed **plant transpiration**). It can also be lost through runoff and deep infiltration through the soil. Total amount of soil water losses associated with both soil evaporation and plant transpiration is referred to as **evapotranspiration**. When irrigation is considered, water losses also include the mismanagement of irrigation water from its source to the crop roots. Usually, more than 50% of irrigation water is 'lost' for the crop at the farm level. However at the watershed level it might be less, due to possible recoveries from the subsoil and groundwater. These off-site losses of water can result from either inappropriate land management practices to capture a substantial part of the rainfall within an agricultural landscape and retain it in the plant rooting zone or excessive use of irrigation water. Such losses not only lead to water wastage but also to potential hazards of soil salinity and water pollution resulting from the transport of nitrate, phosphate, sediments and agro-chemicals to streams, lakes and rivers.

Many promising strategies for raising WUE are available. These include appropriate integrated land–water management practices such as (i) adequate soil fertility to remove nutrient constraints on crop production for every drop of water available through either rainfall or irrigation, (ii) efficient recycling of agricultural wastewater, (iii) soil-water conservation measures through crop residue incorporation, adequate land preparation for crop establishment and rainwater harvesting and (iv) conservation tillage to increase water infiltration, reduce runoff and improve soil moisture storage. In addition, novel irrigation technologies such as supplementary irrigation (some irrigation inputs to supplement inadequate rainfall), deficit irrigation (eliminating irrigation at times that have little impact on yield) and drip irrigation (targeting irrigation water to plant rooting zones) can also minimize soil evaporation thus making more water available for plant transpiration. In much of Sub-Saharan Africa, with sandy soils of low fertility, nutrient deficiencies override water shortages as the main factor limiting crop productivity. Crop growth is so poor that it can only absorb 10 to 15 % of total rainfall, the excess being lost through evaporation, deep percolation and run-off. The resulting WUE can be very low because the amount of water required to produce a person's food diet would be higher than the average value of 2000–5000 kg water/kg food (Fig. I-1). Under these conditions, increasing nutrient supply often leads to an increase in both crop production and WUE [I-1].

Fertigation, which combines irrigation and fertilization, maximizes the synergy between these two agricultural inputs increasing their efficiencies. Overall, improving irrigation WUE, as shown in the Agency's study comparing fertigation against conventional practices in eight of its Member States in West Asia [I-2] will help to minimize FAO's predicted increases in agricultural withdrawals of water.

Nuclear and isotopic techniques can play an important role in improving WUE in agriculture by:

- Improving water management through accurate soil moisture monitoring for optimum irrigation scheduling to minimize water losses.

- Optimizing crop water productivity with more crops per amount of water inputs from rainfall or irrigation.
- Assisting in the selection and evaluation of crop cultivars with tolerance to drought and higher crop water productivity.

The Agency, through both coordinated research projects (CRPs) and projects in its technical cooperation programme (TCP), assists Member States in the use of nuclear and isotopic techniques to enhance WUE through the development of integrated management of soils, crops, water and fertilizer inputs. This review focuses on the role and application of the nuclear and isotopic technologies to address some key issues to improve WUE in agriculture. The applications of nuclear and isotopic technologies are illustrated with results obtained in the FAO/IAEA Programme through CRP and TCP activities.

C. The Soil Moisture Neutron Probe and Stable Isotopes in Improving Water Management

Improving water management in agriculture requires an improvement in soil moisture conservation measures and a reduction in wastage of irrigation

FIG. I-2. A simple technology targeting water to the plant rooting zone to minimize soil evaporation and enhance plant transpiration can improve WUE and increase incomes from cash crops (Courtesy FAO-17075-Peyton Johnson).

FIG. I-3. Furrow irrigation in Uzbekistan; a good water management practice can save a significant amount of the irrigation water.

water. Reduction in water wastage also brings about additional benefits in terms of reducing losses of applied nutrients, water erosion and pollution of surface and ground water. An accurate measurement of soil moisture content and water removal by soil evaporation and plant transpiration processes is therefore essential to establish the optimal soil water balance for crop sowing, fertilizer application and irrigation scheduling under different irrigation technologies, climatic conditions and farm management systems that aim to minimize soil evaporation and increase water accessibility for plant roots (Figs I-2, I-3, I-4). The role of soil moisture neutron probe and stable isotopic techniques in contributing such information will be discussed in the following sections.

FIG. I-4. Irrigation of a potato field in Cape Verde (Courtesy FAO-17075-M. Marzot). It is important to minimize soil evaporation (non-productive) and maximize plant transpiration (productive) components of evapotranspiration.

C.1. Applications of Soil Moisture Neutron Probes

The soil moisture neutron probe (SMNP) is portable equipment for measuring periodically soil water content at different depths through access tubes installed in the soil profile (Fig. I-5). Data generated from this monitoring are used to calculate the soil water balance and estimate the total amount of soil water removed by both soil evaporation and plant transpiration [I-3, I-4, I-5, I-6]. The Agency's activities through CRPs and technical cooperation projects have demonstrated that WUE by crops as measured by the SMNP can be increased by up to 50% by changing irrigation technologies [I-7, I-8] and/or management practices [I-9, I-10] to improve groundcover and thus reduce evaporation from the soil surface. For example, approximately 25–50% of irrigation water can be saved by using drip irrigation (Figs. I-6, I-7) over the traditional flood surface irrigation. Such savings also brought about other benefits including an increase in the efficiency of fertiliser applied to crops to the same extent (20–50%) and a reduction in nitrogen leaching losses beyond the plant rooting zone.

The SMNP, made available in the 1960s, has been a valuable tool for almost 50 years due to its rapid and reliable features that are needed for

FIG. I-5. Scientists from the United Arab Emirates being trained by the IAEA in the use of the SMNP.

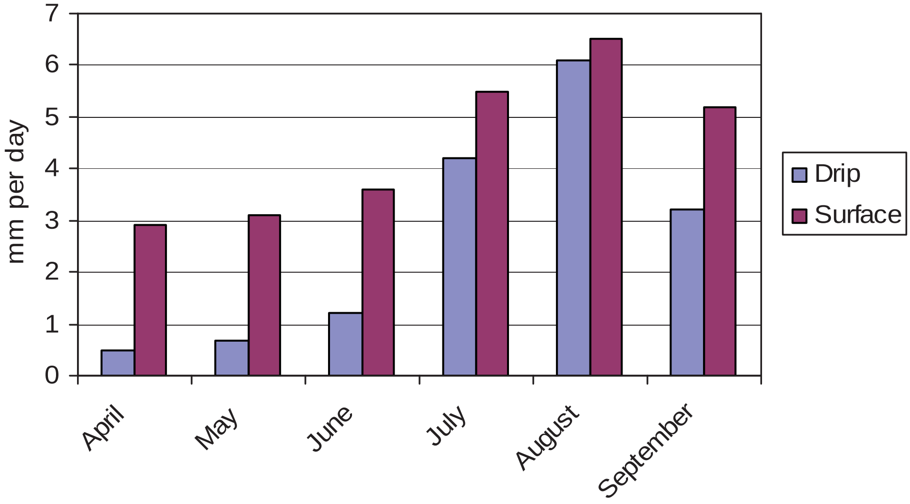

FIG. I-6. Cotton grown in the Syrian Arab Republic: the daily irrigation requirement (mm· day^{-1}) is reported on a monthly basis for drip and surface irrigation. During the first three months of the cropping season, more than 60% of irrigation water can be saved using drip irrigation.

FIG. I-7. A low-cost drip irrigation system being practiced in Sierra Leone (SIL/8/002). Drip irrigation as a means of targeting irrigation water to the main plant rooting zone and avoiding water lost to the atmosphere through evaporation from the soil surface.

frequent and accurate measurement of soil water content. Although other soil monitoring methods have emerged, the SMNP is still relevant in areas where soil conditions such as salinity can affect the accuracy of other equipment [I-11, I-12]. The SMNP consists of two main parts: the probe in its shield and the electronic counting system. The probe contains a sealed radioactive source that emits fast neutrons, and a 'slow neutrons' tube-counter. During measurements, the probe is lowered to the desired soil depth inside an access tube. The fast neutrons are scattered and slowed down in dependence of soil moisture since hydrogen, a component of soil water, is effective at slowing down fast neutrons. The slow neutrons density measured by the counter is directly proportional to the soil water content.

Modern neutron probes have advanced electronics such as microprocessors that utilize factory or user calibration curves to obtain directly soil water content data, which can be stored and then downloaded to a computer at the laboratory [I-12]. Since the SMNP contains a radioactive source, safety and radiation protection rules in the transportation, storage and field use need to be strictly observed, and the Agency has published several documents on these topics [I-11, I-13, I-14] (Fig. I-5).

C.2. Applications of Stable Isotopes in Water Management

Significant advances have been made in the development and application of isotopic techniques in water management in agriculture. The measurement of natural variations in the abundance of stable isotopes of oxygen, hydrogen, carbon and nitrogen in soil, water and plant components can help to identify the sources of water and nutrients used by plants and to quantify water and nutrient fluxes through and beyond the plant rooting zone as influenced by different irrigation and land management practices. These developments have been possible due to the increased sensitivity of continuous flow isotope-ratio mass spectrometers for analysing the isotopic composition in soil–plant–water components. For example, hydrogen and oxygen, as constituents of water can exist as light and heavy isotopes. These isotopes can be used to identify water losses through evaporation from soil surface since the light isotopes (hydrogen-1 and oxygen-16) evaporate more readily than the heavy isotopes (hydrogen-2 {^{2}H} and oxygen-18 {^{18}O}). The natural isotopic ratios of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$), which are often expressed as delta units ($\delta^{2}H$ and $\delta^{18}O$) in soil water, water vapour within a plant canopy and plant leaves can provide estimates of soil evaporation and plant transpiration [I-15, I-16, I-17]. Such information will enable irrigation and land management practices to be developed to minimize soil evaporation (the non-productive loss of water) and channel this water for crop production. Some examples of recent applications of stable isotopes in estimating soil evaporation, plant transpiration and sources of water used by plants are reported below:

- Changes in the isotopic composition of hydrogen (δ^2H) over a ten-day sampling period following surface irrigation of olive trees in Morocco indicated that soil evaporation as a proportion of total water removal (evapotranspiration) from both soil and crops ranged from 0% prior to irrigation to 31% after surface irrigation [I-15]. These results highlight that soil evaporation under the environmental condition studied was substantial, indicating that any management factors that minimize soil evaporation such as drip irrigation can be expected to significantly improve WUE.
- Partition of transpiration from overstory trees from that of understory grasses in the south west of the USA during the post-rainy period by measuring natural variations of both δ^2H and $\delta^{18}O$ indicated that the total water removal (evaporatranspiration) from the ecosystem was 3.5 mm/day of which 70% was from tree transpiration, 15% from the transpiration of grass layer, and 15% from soil evaporation [I-16]. The study highlights that overstory trees can minimize soil evaporation, thus improve the overall WUE of the studied ecosystem.
- Agency sponsored research in a CRP on ‘Use of Nuclear Techniques for Developing Integrated Nutrient and Water Management Practices for Agroforestry Systems’ have demonstrated that natural variation in the abundance of ^2H and ^{18}O in the soil, plant and water can be used to quantify the contribution of hydraulically lifted water from the subsoil (4–5 m) by deep rooting trees growing in association with grasses or crops in the dry savannah regions of Africa (e.g. Burkina Faso and Niger) [I-17]. Hydraulic lift is a process of water movement from subsoil to the topsoil through plant roots. This process could be one of the features contributing to the success of tree-crop association growing in parklands in the dry savannahs of the West African Sahel.

The currently developed FAO crop water productivity model *AquaCrop* [I-18] which aims to predict yield response to water for most major field and vegetable crops under a range of irrigation and land management practices requires a range of data on transpiration and evaporation. These two components of evapotranspiration can be separated by using stable isotopes as outlined above. The planned activities of the Agency in this area will provide valuable information to FAO’s *Aquacrop* model, which will be a useful management tool to manage water in both rainfed and irrigated farming systems around the world.

D. The Use of Carbon Stable Isotopes to Select and Evaluate Drought-tolerant Plant Species

Carbon, the major building block of carbohydrate and proteins in plant tissues contains both light and heavy carbon stable isotopes (^{12}C and ^{13}C). The measurement of natural variations in the abundance of ^{13}C and ^{12}C in plant materials is increasingly being used to select and evaluate plant cultivars that can withstand drought. This technique obviates the need for measurements of the water budgets of a large number of plants during a large scale screening for WUE characteristics. Under drought, less carbon (in the form of carbon dioxide), particularly ^{13}C from the atmosphere is taken up by plants for growth because of plant stress, thus creating a major variation in the natural isotopic ratios of ^{13}C and ^{12}C in plant materials. A plant cultivar, which is resistant to water scarcity should display less depletion in ^{13}C compared with a susceptible cultivar. Such discrimination against ^{13}C (i.e. difference between ^{13}C and ^{12}C, expressed as delta $\delta^{13}C$) in plant tissues (leaves and grains) has been successfully used in the selection of drought-resistant barley, wheat, rice and peanut [I-19, I-20, I-21, I-22, I-23]. Scientists have shown that $\delta^{13}C$ in plant leaves and grain is negatively related to WUE. Besides acting as a surrogate for WUE, carbon isotope discrimination (often abbreviated as CID) measured in different plant parts at harvest can be used as an historical account on how water availability varied during the cropping season [I-24].

The Agency through a CRP 'Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas' has shown that the CID technique was successfully used as a diagnostic tool for predicting WUE and wheat grain yield.[19] A current CRP on 'Selection for greater agronomic water-use efficiency in wheat and rice using carbon isotope discrimination' also established that CID can be used as a selection criterion for wheat yield under a wide range of environmental conditions, in particular under post-flowering stress that represents the most common drought situation. The breeding lines will be further used to develop WUE crop cultivars matching specific environments prevailing in the participating countries.[20]

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19 http://www-naweb.iaea.org/nafa/swmn/crp/d1_2006.html

20 http://www-naweb.iaea.org/nafa/swmn/crp/d1_2008.html

E. Conclusions

The probable advent of increasing water scarcity in this century will see less increase in irrigated land available for food production than in the past. Novel irrigation technologies need to be tested under local environments and particular agricultural production systems of developing countries. While irrigation can benefit yields and enhance WUE in water-limited environments, the potential for full irrigation is decreasing, with increased competition from the domestic and industrial sectors. Thus the main challenge confronting both rainfed and irrigated agriculture is to improve WUE and sustainable water use for agriculture. This can be achieved through: (i) an increase in crop water productivity (an increased in marketable crop yield per unit of water taken up by crop); (ii) a decrease in water outflows from the plant rooting zone other than that required by plants; and (iii) an increase in soil water storage within the plant rooting zone through better soil and water management practices at farm and catchment scales.

Nuclear and isotopic techniques have been shown to be invaluable tools for improving WUE. The SMNP is recognised worldwide as an accurate instrument for measuring/monitoring soil water content. However, licensing, training of users and safety regulations pertaining to the radiation protection measures restricts their use in some situations.

Stable isotopes of water, ^{2}H and ^{18}O, at the natural abundance level; have been used for tracking and quantifying water flows within and beyond the plant rooting zone. These techniques show potential to partition evapotranspiration into soil evaporation and plant transpiration (the water component removed by plants for their growth). Information obtained can then be used: (i) to evaluate the efficacy of different irrigation and land management practices that minimize soil evaporation and optimize plant transpiration; (ii) to locate sources of water use by different plants so as to develop an integrated tree-crop system for sustainable food production particularly in dryland environments; and (iii) to identify and develop management strategies that minimize the losses of water and associated fertilizers, pesticides, soils and animal manure from farm lands. The need to minimize such environmental impact from agricultural activities is increasingly important to enhance viable and sustainable agricultural systems.

The carbon isotope discrimination has potential as a tool for screening and evaluating large samples of cultivars with increased WUE under water-limited conditions.

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Annex II
RADIOPHARMACEUTICALS: PRODUCTION AND AVAILABILITY

A. Introduction

The use of specific radiotracers called radiopharmaceuticals for imaging organ function and disease states is a unique capability of nuclear medicine. Unlike other imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasonography (US), nuclear medicine procedures are capable of mapping physiological function and metabolic activity and thereby giving more specific information about the organ function and dysfunction [II-1]. The mapping of the radiopharmaceutical distribution in vivo provides images of functional morphology of organs in a non-invasive manner and plays an important role in the diagnosis of many common diseases associated with the malfunctioning of organs in the body as well as in the detection of certain type of cancers. The widespread utilization and growing demands for these techniques are directly attributable to the development and availability of a vast range of specific radiopharmaceuticals.

B. Radioisotopes for Radiopharmaceuticals: History and Growth

Radiopharmaceuticals are medicinal formulations containing radioisotopes which are safe for administration in humans for diagnosis or for therapy. Although radiotracers were tried as a therapeutic medicine immediately after the discovery of radioactivity, the first significant applications came much later with the availability of cyclotrons for acceleration of particles to produce radioisotopes. Subsequently, nuclear reactors realized the ability to prepare larger quantities of radioisotopes. Radioiodine (iodine-131), for example, was first introduced in 1946 for the treatment of thyroid cancer, and remains the most efficacious method for the treatment of hyperthyroidism and thyroid cancer.

One of the major goals for setting up nuclear research reactors was for the preparation of radioisotopes. Among the several applications of radioisotopes, medical applications were considered to be of the highest priority. Most of the medium flux and high flux research reactors now are routinely used to produce radioisotopes for medical, and also industrial, applications. The most commonly used reactor produced isotopes in medical applications are molybdenum-99 (for production of technetium-99m), iodine-131, phosphorus-32, chromium-51, strontium-89, samarium-153, rhenium-186 and lutetium-177 [II-2].

FIG. II-1. A 13 MeV cyclotron (indigenous product) in operation in Chosun University, Republic of Korea.

The early use of cyclotrons in the radiopharmaceuticals field was for the production of long lived radioisotopes that can be used to prepare tracers for diagnostic imaging. For this, medium to high energy (20–70 MeV) cyclotrons with high beam currents were needed. Isotopes such as thallium-201, iodine-123 and indium-111 were prepared for use with single photon emission computed tomography (SPECT). With the advent of positron emission tomography (PET), there has been a surge in the production of low energy cyclotrons (9-19 MeV) exclusively for the production of short lived PET radionuclides such as fluorine-18, carbon-11, nitrogen-13 and oxygen-15. Figure II-1 shows such a machine. The majority of the cyclotrons (~350) worldwide are now used for the preparation of fluorine-18 for making radiolabelled glucose for medical imaging [II-3].

C. Radiopharmaceuticals Production Aspects and Challenges

Currently there are over 100 radiopharmaceuticals developed using either reactor or cyclotron produced radioisotopes and which are used for the diagnosis of several common diseases and the therapy of a few selected diseases, including cancer. Radiopharmaceuticals production involves handling of large quantities of radioactive substances and chemical processing. Aspects which need to be addressed in radiopharmaceuticals production, including the management of radioisotope production, include import, operation and

FIG. II-2. Hot cells with manipulators used for radioisotopes/radiopharmaceuticals production available from commercial sources.

maintenance of processing facilities, complying with the codes of current good manufacturing practices (cGMP), ensuring effective quality assurance and quality control (QA & QC) systems, registration of the products with national/ regional health authorities and radioactive material transport etc.

Radiopharmaceuticals production, unlike conventional pharmaceuticals production, is still on a relatively small scale and implementing the cGMP guidelines which are applicable for the drugs industry is both difficult and expensive. Ensuring cGMP compliance is a demanding task for a small scale manufacturer, as it involves taking care of several aspects prior to, during and after production. These include the development of well qualified personnel, use of controlled materials and procedures, availability of qualified equipment, production of the products in designated clean areas, applying validated processes and analytical methods, full documentation of the process and release of the final product by a qualified person. Application of clean room requirements in radioisotope laboratories in general and hot cells in particular (Fig. II-2), is technically demanding to be compatible with the requirements for both radiological and pharmaceutical safety. The Agency assists its Member States to improve the radiopharmaceuticals production to meet cGMP as adaptable to radioactive products by providing appropriate documents, conducting training courses and supporting technical cooperation projects [II-4].

The last decade has seen an increase in the use of PET in regular diagnostic imaging, and a commensurate use of PET radiopharmaceuticals, particularly fluorine-18 in the form of fluorodeoxy glucose (^{18}F-FDG). The

FIG. II-3. A ^{99}Mo-^{99m}Tc generator production facility built under an IAEA technical cooperation project in Bangladesh.

associated 511 keV high-energy radiation needs thicker shielding and more sophisticated handling devices. In view of the short half-lives, the emphasis is also increasingly on process validation and strict adherence to approved procedures in handling of all steps of manufacture, rather than relying on the final QC test results alone. The need for rapid, remote and reliable synthesis of PET radiopharmaceuticals has led to the introduction of microprocessor controlled automated synthesis modules. This experience has also led to the development of similar automated synthesis module systems for other radiopharmaceuticals.

D. Technetium-99m Radiopharmaceuticals and their Kits

Technetium-99m is the most widely used radioisotope in diagnostic nuclear medicine, it being estimated that over 80% of the nearly 25 million diagnostic nuclear medicine studies carried out annually are done with this single isotope. This percentage share is expected to remain for the foreseeable future, notwithstanding the introduction of new diagnostic radiopharmaceuticals with other radionuclides. The availability of the short lived technetium-99m (a half-life of 6 hours) as the daughter product of the long lived molybdenum-99 (a half-life of 66 hours) is one of the major factors which have promoted the universal use of this radioisotope. The Agency has supported Member States in the local production of molybdenum-99–technetium-99m generator technologies, thereby enhancing the availability of technetium-99m for diagnostic studies (Fig. II-3).

The parent radionuclide molybdenum-99 can be prepared in abundant quantities by the fission of uranium-235 in a nuclear reactor with a fission yield of about 6%. There are only a limited number of industrial companies and national centres producing molybdenum-99 from fission products, but collectively they have adequate capacity to meet the world's demands for molybdenum-99. More than 95% of the molybdenum is currently produced using high enriched uranium (HEU) targets. At the request of concerned Member States, the Agency is supporting the adaptation of technology for the production of molybdenum-99 using low enriched uranium targets.

Technetium-99m radiopharmaceuticals are often formulated from cold kits, so called because they do not contain radioactivity. When treated with sodium pertechnetate solution eluted from a technetium-99m generator, the final product for patient injection is directly formed. Cold kits are prepared in such a manner as to have a long shelf life, ranging from several months to a few years, and may be transported at room temperature and then stored under refrigeration to ensure stability. Large-scale preparation of the cold kits requires special techniques and facilities and is mostly done by industrial companies and in national laboratories. The IAEA has supported a number of developing Member States in setting up cold kit production facilities through technical cooperation programmes as well as by developing and transferring technical know-how through various coordinated research projects.

E. Diagnostic Uses of Technetium-99m Radiopharmaceuticals

The early technetium radiopharmaceuticals were developed by taking advantage of physiological properties such as adsorption, distribution, metabolism and excretion of various technetium-99m complexes, and were used for imaging the thyroid, liver, bone, kidneys etc. Careful design of new technetium-99m complexes led to the discovery of agents for imaging the blood flow (perfusion) in the muscular tissue of the heart (myocardium) and the brain. Currently, SPECT imaging using technetium-99m products is often an important component of evaluation of patients with known or suspected coronary artery diseases.

The primary role of radiopharmaceuticals in cancer treatment will be towards the follow-up of patients with a known disease. Technetium-99m–MDP (methylene diphophonate) is a widely used radiopharmaceutical to detect bone metastasis associated with many forms of cancer. It has also been discovered that some of the technetium-99 radiopharmaceuticals used for renal and cardiac studies also accumulate in some forms of primary cancer, which has led to the use of technetium-99m radiopharmaceuticals for imaging primary cancer other than that of the thyroid. A majority of current investigations in development of cancer imaging agents mostly use peptides and antibodies as carrier molecules to target tumour sites. Radiopharmaceuticals can provide useful information about the function and molecular biology of the tumour by measuring several of the causal factors of the tumour. In future, specific roles of technetium-99m radiopharmaceuticals for imaging in oncology may include for example, the lymphatic system, development of new blood vessels and monitoring gene therapy.

Currently an area of high interest is for developing technetium-99m products for SPECT imaging of receptors in brain which would help managing patients with movement disorders. Advances in novel labelling techniques and identification of appropriate carrier molecules have strengthened the efforts in this direction.

F. Radiopharmaceuticals for Positron Emission Tomography Imaging

The evolution of PET as a clinically useful imaging modality has its origin in the synthesis of fluorine-18 fluorodeoxyglucose (^{18}F-FDG) in 1976 at the Brookhaven National Laboratory. Fluorine-18 is the positron emitting radioisotope. The initial application of ^{18}F-FDG was for mapping glucose metabolism in the brain in the understanding and monitoring neurological diseases. While it is also useful for studying myocardial viability, due to the greater utilisation of glucose by the proliferating cells, the major use of ^{18}F-FDG subsequently emerged in the detection, staging and treatment follow up of various types of cancers. Currently PET studies using ^{18}F-FDG account for 10% of all imaging performed using radiopharmaceuticals. A number of other fluorine-18 labelled radiopharmaceuticals are being developed and a few of them are under clinical investigations [II-1].

Increasing clinical demand for ^{18}F-FDG has triggered technological advances in various fields such as accelerator technology, radiochemistry, automated processing modules, detector systems, and imaging software. A typical cyclotron-PET centre nowadays includes a dedicated medical cyclotron together with automated radiochemistry modules and a number of PET or PET-CT units. Daily large scale production of ^{18}F-FDG in the early morning hours for extensive and rapid distribution to medical centres is becoming common practice in several countries.

F.1. Generator Produced PET radiopharmaceuticals

The availability of PET radionuclide generators would facilitate PET studies by those centres that do not have a cyclotron. In addition, it can also enhance the range of studies at existing cyclotron/PET centres. The PET isotope gallium-98 can be obtained from germanium-68–gallium-68 generator. The parent germanium-68 prepared using 30-60 MeV energy and high current cyclotron has a long half life (271 days) and hence the generator can be transported over very long distances and useful for periods of up to one year. In addition to infection imaging, gallium-68 is finding use in cancer imaging when labelled with peptides. The ultra short-lived rubidium-82 (a half-life of 75 seconds), available from a strontium-82–rubidium-82 generator, and useful for PET imaging of blood flow to myocardium, has high potential in managing heart patients.

G. Therapeutic Radiopharmaceuticals

Radionuclide therapy employing radiopharmaceuticals labelled with beta emitting radionuclides is emerging as an important part of nuclear medicine. In addition to the management of thyroid cancer, radionuclide therapy is utilized for bone pain palliation, providing significant improvement in the quality of life of cancer patients suffering from pain associated with bone metastasis as well as for the treatment of joint pain, as in rheumatoid arthritis. Though the sale of therapeutic radiopharmaceuticals is currently much lower compared to that of diagnostic products, a steep increase over the next 5-6 years is predicted [II-5, II-6], since several new products for treating lymphoma, colon cancer, lung cancer, prostate cancer, bone cancer and other persistent cancers are expected to enter the market. Development of sophisticated molecular carriers and the availability of radionuclides in high purity and adequate specific activity are contributing towards the successful application of radionuclide therapy.

G.1. Radiopharmaceuticals for Bone Pain Palliation

Persons suffering from breast, lung and prostate cancer develop metastasis in bones in the advanced stage of their diseases and therapeutic radiopharmaceuticals containing radionuclides such as strontium-89, samarium-153 and rhenium-186/188 are used for effective palliation of pain from skeletal metastases. The IAEA has initiated a programme for the development and clinical application of lutetium-177 based radiopharmaceuticals for bone pain palliation. It can be prepared in large quantities for bone pain palliation application in low/medium flux research reactors, which are available in several countries. The long half-life of lutetium-177 provides logistic advantages for production and testing of the products as well as the feasibility to supply the products to places far away from the production site.

G.2. Radiopharmaceuticals for Primary Cancer Treatment

Targeted radionuclide therapy involves the use of radiopharmaceuticals to selectively deliver cytotoxic (toxic to cells) levels of radiation to a disease site, as this would potentially deliver the absorbed radiation dose more selectively to cancerous tissues. Advances in tumour biology, recombinant antibody technology, solid phase peptide synthesis and radiopharmaceuticals chemistry have led to investigations on several new radiotherapeutic agents. Radiolabelled peptides as molecular vectors are being developed for targeted therapy. When labelled with therapeutic radionuclides, peptide molecules have the potential to destroy receptor-expressing tumours, an approach referred to as peptide receptor radionuclide therapy (PRRT). Yttrium-90 and lutetium-177 are frequently used as radionuclides in such PRRT studies.

During the development, the assessment of the relative effectiveness of different radiopharmaceuticals for cancer therapy is complex because of the large number of variables to be considered, some related to the biological carrier and others to the radioisotope. Comparing the therapeutic efficacy in patients is not feasible in most cases, and so development of laboratory methods that can be used for reliable and efficient comparative evaluation of promising therapeutic radiopharmaceuticals is an important need.

G.3. Radiopharmaceuticals for Radiosynoviorthesis

Radiosynoviorthesis or radiosynovectomy is a technique wherein a radiopharmaceutical is delivered into the affected synovial compartment (the interior of joints that is lubricated by fluid) of patients suffering from joint pain, as in the case of rheumatoid arthritis. Beta-emitting radiolabelled colloids are widely used for this purpose. Several radiopharmaceuticals have been developed using phosphorus-32, yttrium-90, samarium-153, holmium-166, erbium-169, lutetium-177, rhenium-186, etc. and some of them are registered for human use. The radiation properties of each therapeutic isotope determine their respective use and applicability for the joint size.

H. Radiopharmaceuticals Market and Future Trends

A number of Member States through the Agency's technical cooperation programme have developed capacities for radiopharmaceuticals production, manufacturing products regularly to meet local demands. The assured local availability of radiopharmaceuticals has greatly contributed to the growth of nuclear medicine practices in such countries, in addition to ensuring price stability of radiopharmaceuticals imported from large manufacturers. Local production and distribution of radiopharmaceuticals has also helped to reduce the number of radioactive consignments that need to be transported across international borders.

Problems and delays in transport of radioactive materials; the need for compliance with transport regulations; the denial of shipments by some carriers etc., often affect the end use of the imported products. For example, if a shipment of the raw material molybdenum-99 is affected by any delay, it leads to a cascading negative impact, as several users of technetium-99m generators are then affected for the subsequent period. Some countries follow a practice of holding up all the cargo in airports at times for a pre-destined period (say 24 to 48 hours) before being loaded on the plane, as part of measures for enhancing security. This procedure also affects the radiopharmaceuticals due to additional decay losses apart from the delays caused, especially when dealing with short-lived radioactive materials. The decay loss during a 'cooling' (waiting) period of 24 hours amounts to nearly 20 to 22% of radioactivity in the case of thallium-201 and technetium-99m generator consignments, in addition to causing disruptions to the patient appointments. The IAEA has hence tried to create necessary awareness through informed discussions towards better understanding of the various aspects involved, so that denials and delays in shipments of radioactive materials are not unduly affecting the availability and use of radiopharmaceuticals.

A process of formal 'Approval or Registration' after screening by competent national authorities is necessary for marketing authorisation of radiopharmaceuticals, for both those produced locally and imported from commercial sources. For example, centralised radiopharmacy units in Scandinavia, usually under the auspices of the drug administration authority, carry the responsibility for the control and supply of radiopharmaceuticals around the country. All radiopharmaceuticals which are to be procured or imported are formally assessed before being passed on to the end-users. The Good Manufacturing Practice (GMP) status of each supplier is to be established and a dossier on each product submitted as a pre-requisite before entry into distribution chain. Such a system could be very useful for many Member States that at present do not have a formal market authorization system in place for radiopharmaceuticals, as even smaller countries benefit from similar approaches. Those countries that already have formal systems paralleling normal medicines are increasingly feeling the impact of the present prohibitive costs associated with formal market authorisation process for radiopharmaceuticals.

There is a considerable variation in the extent of local availability and utilisation of radiopharmaceuticals in different parts of the world. However, consistent with an overall growth in health care systems in many developing economies, the demands for the use of diagnostic and therapeutic radiopharmaceuticals are increasing including in developing countries and in turn, in the number of requests for strengthening capabilities through the Agency's technical cooperation support.

I. Centralized Radiopharmacy Services

Radiopharmaceuticals, unlike normal medicines which once produced undergo total quality control assessment before they reach the public, do not go through such procedures, especially the short-lived products prepared at the users' end. There is thus complete reliance on the robustness of quality assurance systems for the radiopharmaceutical release for patient administration to insure patient safety.

At a busy hospital level, the preparation of radiopharmaceuticals mostly involving the radioisotope technetium-99m, which has a half life of 6 hours, is done by the addition of technetium-99m from approved radioisotope generators to pre-sterile, validated approved commercial kits (see paragraph D. above) The process of simple 'shake, mix or even heat' radiopharmaceutical formulation can technically be performed in a busy clinical setting. These radiopharmaceutical medicines are therefore mainly assembled within the conditions of the approved kit on-site in 'Hot Laboratory Radiopharmacy' for use within the hospital [II-7, II-8]. Under such a scheme, radiopharmaceutical injections are provided daily in accordance with their quality assurance systems. Any deviation from the approved method of preparation would require considerable validation before patient use.

Increasingly the national authorities in some Member States are requiring that this preparation be undertaken in compliance with GMP (good manufacturing practices) conditions overseen by a state registered pharmacist or 'Authorized person/Qualified person'. To address these requirements, nuclear medicine physicians are recommending the setting up of centralized radiopharmacies. In larger cities instead of each clinical nuclear medicine department having their own 'Hot Laboratory', investment is recommended for the setting up of a self-funded, partially commercially supported, or totally

FIG. II-4. Value added services e.g. radiolabelled white cells for infection imaging. Aseptic preparation by trained staff under Laminar flow hood — Kars El-Einy Nuclear Medicine Department, Cairo, Egypt.

private operated centralized radiopharmacy service [II-7, II-8]. Both from a legal and quality assurance perspective, the responsibility for the quality of the radiopharmaceutical then lies in the hands of the radiopharmacy.

Experience from such a model of a centralized radiopharmacy service suggests many advantages, such as delivery of the best products from all sources and services available; more efficient use of human resources; ability to dispense patient specific prescription; minimization of radiation exposure; simplification of regulatory and practice-based paperwork; maintenance of quality assurance requirements and reduction of risk, e.g. radioiodine capsules; additional services, e.g. white cell labelling for infection imaging (Fig. II-4); same day delivery of products; simpler retrieval of radioactive waste and the maintenance of continuous and immediate pharmacy services.

The overall impact of recent trends and changes in health care economics and operational viability of hospitals will result in nuclear medicine practitioners looking to the centralized radiopharmacies to meet a larger portion of their radiopharmaceutical needs, as well as to value added services, such as education and research and development.

In Europe, centralized systems are driven more by the needs in meeting regulatory demands than by commercial interests alone, as the supplies from radiopharmacies are required to meet full GMP compliance, even for technetium-99m labelled radiopharmaceuticals.

A somewhat different situation for PET and other short lived radiopharmaceuticals applies. Regulatory authorities require high standards of compliance, independent of whether production is centralized or local.

Decentralised systems in this respect are necessary and play an essential role in clinical research in nuclear medicine, particularly if extremely short lived diagnostic radiopharmaceuticals labelled with carbon-11 or oxygen-15 are employed, and for the exploration of radiopharmaceuticals for therapeutic applications. Limitations of a centralised production system are the reduced flexibility for the nuclear medicine department to respond to acute clinical demand, and this situation will remain for ultra-short lived radionuclides and in the development or research activity for new radiopharmaceuticals.

There are increasing calls for radiopharmaceutical regulations, from both administrators and legislators in many countries, including the regulations for PET and for clinical trials. Whether this increase in regulation leads to a significant change in practice from decentralised to centralized radiopharmacy, based on commercial, semi-commercial or 'not for profit' co-operative models, remains to be seen. In the future, trends indicate that nuclear medicine practitioners will look to the centralized radiopharmacy model for an increasing portion of their radiopharmaceutical needs, with manufacturers ready and able to meet demands in a safe, timely, and cost efficient manner.

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Annex III
USING ISOTOPES TO UNDERSTAND THE OCEANS AND CLIMATE CHANGE

A. Introduction

The ocean plays a critical role in modulating the earth's climate. Recent human influence has caused the ocean to absorb additional heat and CO_2, because of the increase in atmospheric CO_2. The oceans absorb CO_2 through physical as well as biological processes. Over the last 50 years radionuclides from both natural and anthropogenic sources have served as sensitive and increasingly indispensable tracers of ocean processes that are important in regulating climate change. Marine scientists have also applied various isotopic techniques to understand the sources, pathways, dynamics, and fate of carbon, as well as pollutants and particles that enter the oceans from land or atmosphere. For example, radiocarbon (^{14}C) and tritium (^{3}H) have been used to determine sources, ages, and pathways of great ocean currents and water masses; carbon-13 (^{13}C), nitrogen-15 (^{15}N), and phosphorus-32 (^{32}P) have served to map ocean productivity and to track the transfer of CO_2 to seawater, marine biota, and organic compounds.

This annex focuses on the diagnostic value of natural and anthropogenic isotopes to track ocean circulation and cycling of carbon, and to verify global ocean models which underpin future climate predictions and impacts.

B. Ocean Circulation

The major circulation patterns of the global ocean are shown in Fig III-1. Large-scale currents are driven by winds as well as seawater density differences arising from changes in salinity and temperature. Cold and dense surface waters in the North Atlantic and Antarctic sink to depths up to 4000 m and travel as submarine currents into the Atlantic, Indian, and Pacific Oceans (blue and purple). This loop is completed as the effects of winds and the exchange of heat and freshwater drive warm surface currents (red) back to the Atlantic Ocean.

Radiocarbon measurements indicate that ages of deep waters increase from about 100 years for the North Atlantic to about 2000 years in the North Pacific. This 'slow' circulation regime nevertheless moves and mixes 900 000 gigatonnes of water per year, equivalent to 30 times the global river flow. This 'ocean conveyor belt' also transports many gigatonnes of carbon and nutrients

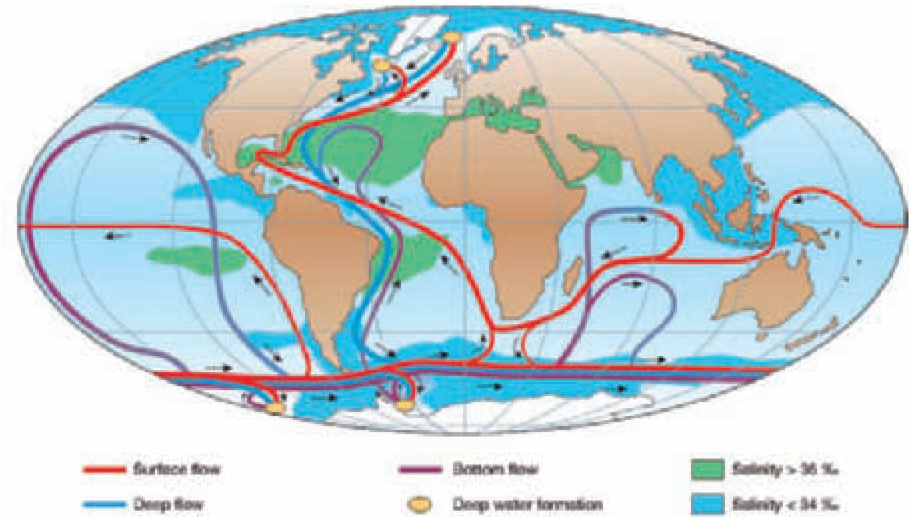

FIG. III-1. The major global ocean currents that make up the ocean's thermohaline circulation, which is driven by winds and differences in salinity and temperature due to exchange of heat and freshwater. Source: after Rahmstorf (2002).

which are vital for life. Enormous quantities of heat are also redistributed. For example, in the North Atlantic, the northward flowing warm surface currents, including the Gulf Stream, provide heat to northwest Europe of more than one Petawatt, which is equivalent to the energy output from more than one million 1 GW nuclear power plants.

B.1. Natural Isotopes in the Oceans

B.1.1. Natural Radiocarbon

Oceanic measurements of ^{14}C include both a natural component and a nuclear-era (anthropogenic or bomb) component. Natural ^{14}C is produced in the atmosphere by cosmic ray interactions to produce $^{14}CO_2$ gas, much of which is then absorbed by the ocean. Naturally produced ^{14}C is useful to evaluate circulation and ventilation of ocean waters below 1000 metres, where there is little contamination by weapons origin ^{14}C. Naturally produced ^{14}C is particularly useful because it exhibits horizontal and vertical gradients in the deep ocean due to a combination of its radioactive decay (half-life of 5730 years) and the slow mixing and ventilation of deep-ocean waters (100 to 1000 years). Thus natural ^{14}C provides a means to clock deep-ocean circulation, unlike tracers such as temperature and salinity. This enables scientists not only to derive the

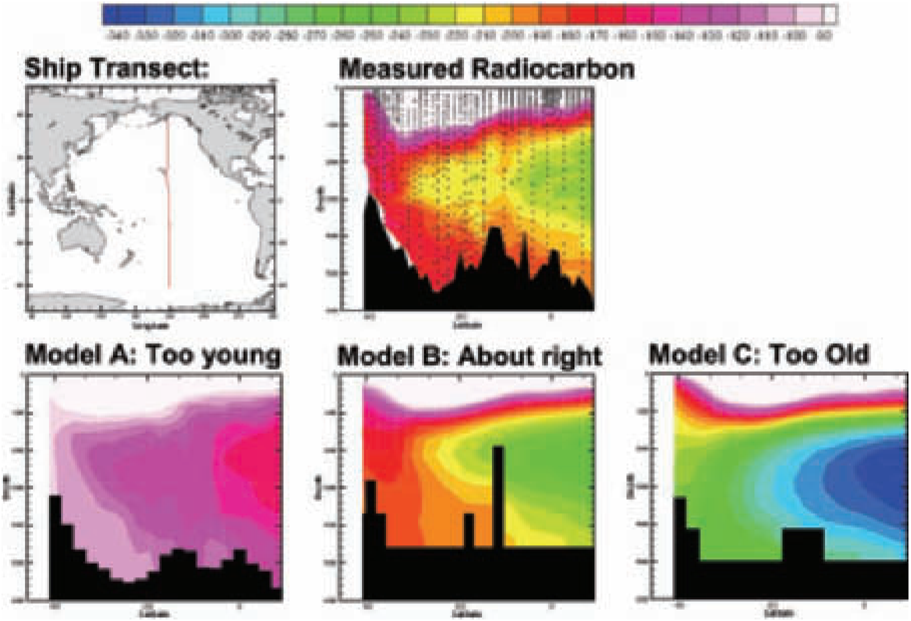

FIG. III-2. Comparison of observed vs. modelled $\Delta^{14}C$ along the World Ocean Circulation Experiment (WOCE) ship track P16 in the central Pacific. The top left slide shows this north-to-south sampling line down the middle of the Pacific Ocean. Just to the right, is the corresponding latitude-depth section of $\Delta^{14}C$ data from the Antarctic to the Alaska. In the bottom row are three ocean circulation model simulations: model A is too young, model B is about right, and model C is too old relative to the Pacific $\Delta^{14}C$ data.

sources and ages of deep water masses but also to check the accuracy of global ocean circulation models. For instance, Fig. III-2 shows a comparison of observed and modelled natural ^{14}C along a north-to-south ship transect located in the centre of the Pacific Ocean.

B.1.2. Helium-3

As opposed to the relatively homogeneous sea-surface input of ^{14}C, helium-3 (^{3}He) in the ocean is injected along deep ocean ridges. These deep-ocean hydrothermal sources provide a unique marker of deep-ocean circulation, and in particular the direction and dispersion of deep currents (see Fig. III-3). It was recently found that oceanographic circulation patterns deduced from ^{3}He data contradicted the classic model of deep-ocean circulation. It became obvious to many that the unique features of ^{3}He could shed much light on the mysteries of deep-ocean circulation. However, our insight

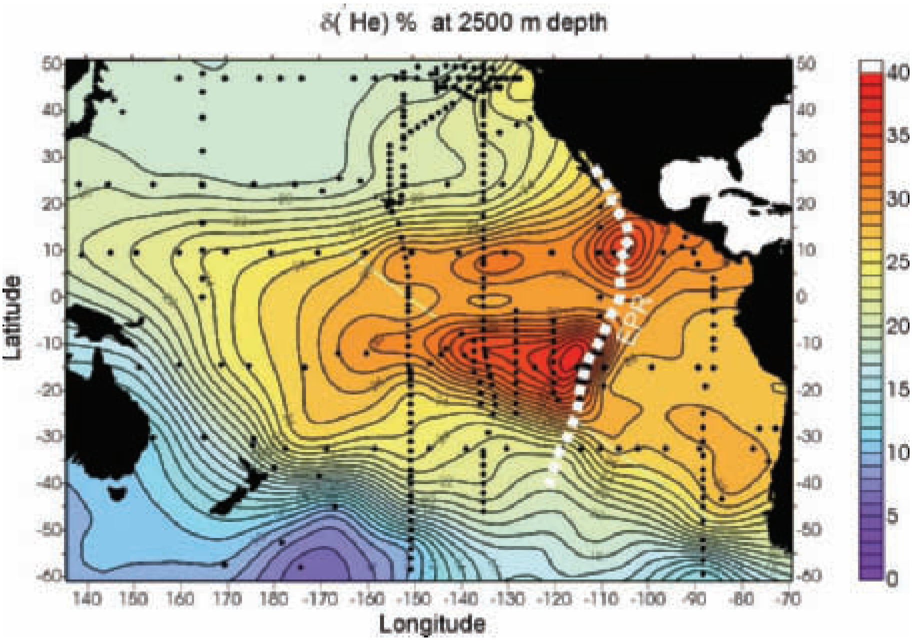

FIG. III-3. Map of δ^3He at a depth of 2500 m in the Pacific. Two helium plumes extend westward from the ridge axis of the East Pacific Rise (EPR). Credit: John Lupton NOAA/PMEL.

remains limited by the spatial variability and unknown intensity of ^{3}He sources along ocean ridges. Consequently, oceanographers are starting to use ^{14}C-calibrated circulation models to back-calculate the source location and inputs of ^{3}He needed to account for the worldwide database of ^{3}He measurements. Applying a similar 'inverse modelling' strategy to other data, such as to measurements of a contaminant in the deep-ocean, could perhaps be useful in identifying its source, such as near old radioactive dump sites in the north-eastern Atlantic.

B.1.3. Uranium and Thorium Decay Series

Natural radioactivity in seawater is primarily derived from the three primordial radioactive parents, uranium-238 (^{238}U), uranium-235 (^{235}U) and thorium-232 (^{232}Th), which yield over 22 radioactive daughter products with widely different half-lives and reactivities. Along each of these three natural radioactive decay pathways, soluble species, such as uranium, often decay to particle reactive species, such as thorium; one also finds the opposite tendency of a particle reactive species decaying to a soluble species. These discrepancies in particle reactivity lead to 'secular disequilibrium' and dramatically different distributions in the water column. Oceanographers have exploited these particle-scavenged 'clocks' to derive information on sources and fluxes of marine and terrestrial particles, carbon, and gases as well as on inputs and stirring rates of the present and past ocean.

The oceanic dispersion and sedimentation of mineral and biogenic particles and the reactivities of these particles with dissolved chemicals help regulate the long-term fate of carbon and related elements, including oxygen and nutrients. Consequently, it is expected that uranium and thorium derived rates of particle dynamics will increasingly underpin future ocean climate models, particularly for simulation of large-scale erosion, carbon-sequestration, and biological changes under future greenhouse scenarios.

B.2. Anthropogenic Isotopes in the Ocean

B.2.1. Weapons Testing Derived

The world-wide fallout of anthropogenic radionuclides from atmospheric testing of nuclear weapons peaked in the early 1960s and has since dispersed and been diluted in the marine environment. Although resulting inputs of ^{3}H, ^{14}C, strontium-90 (^{90}Sr), caesium-137 (^{137}Cs), and plutonium (Pu) isotopes can still be detected 50 years later throughout much of the marine ecosystem, the radiological dose to humans from seafood consumption is typically one hundredth that resulting from naturally occurring radionuclides. Marine scientists have exploited this global-scale, pulse-like input along with the different behaviours of these radioisotopes to trace and clock both small-scale near-shore and large-scale oceanic process including circulation, sedimentation, and biological productivity.

Weapons Radiocarbon

A much used tracer of ocean circulation is the ^{14}C that is derived from atmospheric weapons tests, which increased atmospheric ^{14}C up to nearly twice its natural level before it declined again after 1963 due to implementation of test ban treaties. Bomb and natural ^{14}C are distinguished in the ocean by comparisons with other chemical and isotopic markers. Oceanographers have been able to use the weapons test ^{14}C signal, which has penetrated the upper 1000 m of the ocean, to validate surface circulation fields simulated by ocean models. General patterns between models and data are similar, with lows in equatorial and high latitude regions and highs in the subtropics. The differences evident between models and data for some regions (e.g. western boundary currents, north Pacific) call for better and finer scale models in these areas. Bomb ^{14}C also serves as a marker of recent carbon inputs including the concurrent invasion of anthropogenic CO_2, which originates mainly from combustion of fossil fuels.

Weapons Tritium

Like ^{14}C, tritium is produced naturally in the upper atmosphere and brought to the earth's surface as rain and snow. In addition, weapons testing injected large quantities of tritium into the atmosphere. Bomb tritium levels overwhelm natural levels throughout the upper 1000 m of the ocean. Thus bomb tritium has been used not only to track shallow water masses but also to date them by exploiting tritium's 12.3-year half-life. Tritium measurements have provided the clearest demonstration yet of the decadal-scale progress of cold sub-polar waters sinking into the deep North Atlantic. Tritium releases from nuclear power plants have also been used to clock dispersion in coastal shelf seas.

Other Tracers

Other anthropogenic, bomb-produced tracers (including ^{90}Sr, ^{137}Cs and plutonium isotopes) have not been measured as systematically throughout the world's ocean. However, their unique marine chemical properties are starting to be exploited by some ocean modellers in attempts to evaluate and improve simulations of the movement and fate of sediments, nutrients, and pollutants at both regional and global scales.

C. Ocean Uptake of CO_2 and its Impacts

C.1. Global Carbon Cycle

The present day reservoirs and flows of natural and anthropogenic carbon are summarised in Fig. III-4. Time series measurements of atmospheric CO_2 have revealed an exponential increase from 280 parts per million (ppm) to 380 ppm since industrialisation began in 19th century. Carbon dioxide is the primary greenhouse gas after water vapour that regulates the global heat balance on earth. The ocean absorbs CO_2 through physical as well as biological processes, namely through photosynthesis by microalgae (phytoplankton), ingestion of phytoplankton by microscopic animals (zooplankton), and eventual settling of that carbon into the abyss. The infiltration of anthropogenic

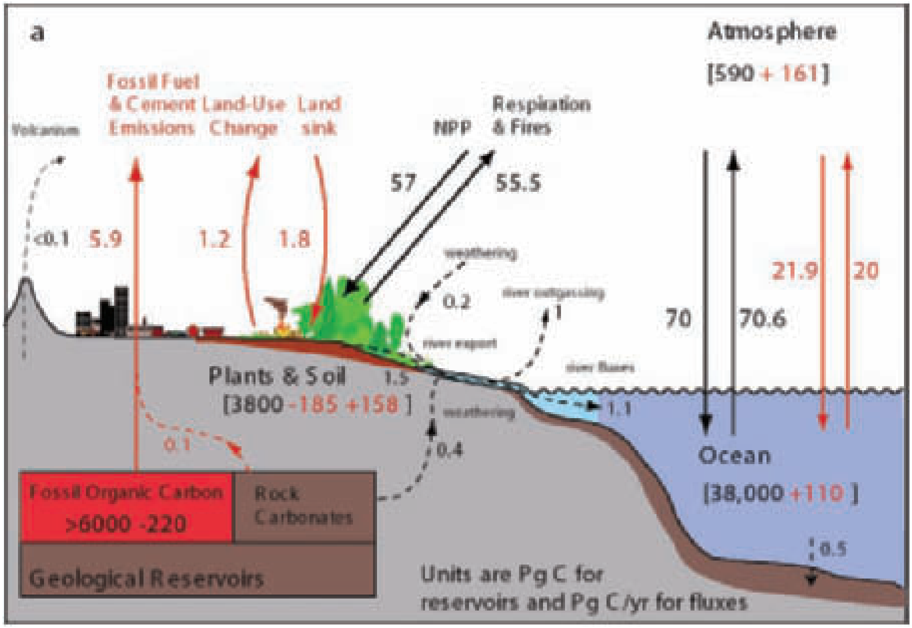

FIG. III-4. Illustration of the carbon cycle's major reservoirs and the fluxes between them, including both the natural (black) and anthropogenic components (red). Anthropogenic components are averages for the 1980's and 1990's. Units are in gigatonnes C for reservoirs and in gigatonnes C per year for fluxes). Emissions of CO_2 from cement production amount to about 10% of the fossil fuel CO_2 emissions. NPP is net primary production due to terrestrial plant photosynthesis. Source: Sabine et al. 2004

CO_2 into the ocean, which is due to physical processes, has been tracked by ocean measurements of carbon isotopes (^{12}C, ^{13}C, and ^{14}C). These isotopic data indicate that the ocean is currently absorbing about 2 gigatonnes per year of anthropogenic CO_2, which is about one third of the total annual anthropogenic CO_2 emissions from fossil fuel burning and deforestation.

Furthermore, ocean carbon isotope measurements have revealed regional differences in the ocean's CO_2 storage capacity. Similarities between the infiltration of anthropogenic CO_2 into the ocean and corresponding anthropogenic changes in $^{14}C/^{12}C$ and $^{13}C/^{12}C$ make these isotopes particularly appropriate for evaluating and improving numerical models designed to quantify past, present, and future ocean carbon uptake.

C.2. Acidification of the Ocean

The ocean's vast capacity to absorb CO_2 is largely due to its natural abundance of carbonate ion, an antacid that neutralizes CO_2 as it enters the surface ocean from the atmosphere. As atmospheric CO_2 levels continue to increase, present-day ocean carbonate ion concentrations are being lowered along with seawater pH due to a process known as ocean acidification. Over the last 20 years, reductions in ocean pH have been documented by direct measurements in the Atlantic and Pacific Oceans. Surface ocean pH has declined by 0.1 unit since the onset of the industrial revolution; most of that change occurring over the last 30 years. By the end of this century, surface ocean pH will drop by another 0.3 to 0.4 units, which represents a 100 to 150% increase in hydrogen ion concentration. The amount of human-made anthropogenic CO_2 that is going into the ocean, currently 4 kg per person per day, is already suspected to be affecting marine life. During the 21st century, corals and other calcifying organisms may suffer a great decline. As carbonate ion concentrations drop, calcifying organisms have more trouble forming their essential skeletal or shell material out of calcium carbonate. Eventually calcification rates, which are often measured by addition of the radiotracer calcium-45, could slow to the point where they are outpaced by erosion and organisms would simply fade away. Corals provide fish habitat and breeding grounds, defence against storms and erosion, and underpin a multi-billion dollar tourism industry. Ocean acidification will have pervasive impacts on marine organisms, food webs, and toxicity of pollutants, such as heavy metals. Marine radioecological studies conducted under high CO_2 scenarios will help unravel some of the long-term effects of ocean acidification.

D. Biological Cycling of Carbon

D.1. Tracking Carbon Export and Burial in Deep Sediments

Phytoplankton assimilate inorganic carbon dissolved in the surrounding seawater and transform it into organic carbon within their cells, leading to a decrease in CO_2 concentration, which promotes further transfer of CO_2 from the atmosphere to the surface ocean. Phytoplankton lie at the base of the food chain and are grazed by marine zooplankton. These tiny surface-dwelling animals ingest phytoplanktonic carbon for energy, while packaging their carbon waste into faecal material that is excreted and settles into the deep ocean. Thus carbon is pumped from the atmosphere through the surface ocean and into the deep ocean as organic carbon. This transfer is facilitated because

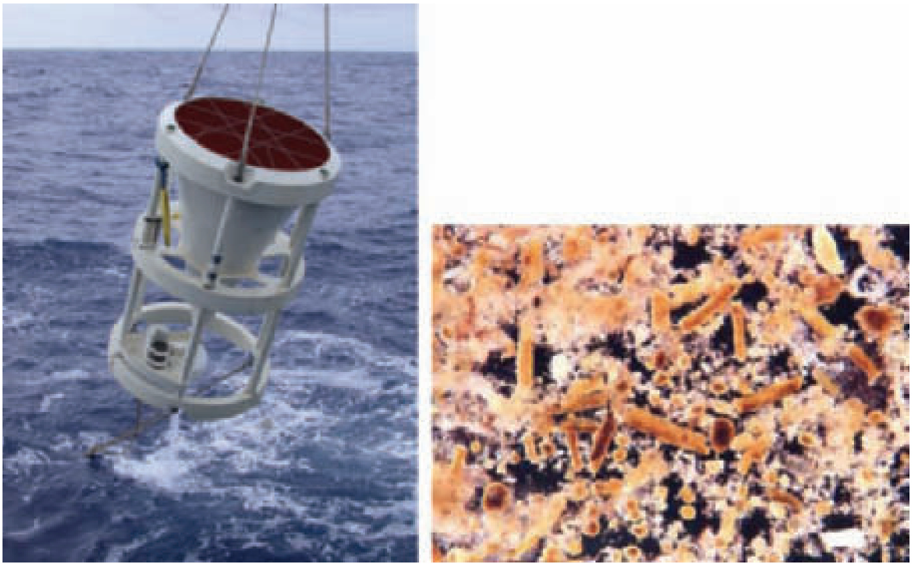

FIG. III-5. Sediment trap (left) used to catch marine particles (right) that settle from the surface to the deep ocean.

ingested or dying plankton also contribute dense silica (diatoms) or calcium carbonate material from their tiny shells, which helps to send particles further into the abyss. Once the organic carbon and calcium carbonate particles reach the ocean interior they remain isolated from the atmosphere for centuries. A small portion even becomes incorporated into marine sediments. This vertical carbon-transport process, termed the 'biological pump', naturally keeps atmospheric CO_2 levels lower by concentrating carbon in the deep ocean.

Two complementary approaches have been used to quantify the flux of carbon and sinking particles in the oceans. Firstly, in order to capture particles as they fall from the surface to the deep ocean, large conical or cylindrical traps have been deployed. These sediment traps (Fig. III-5) are either set adrift to float for a few days at a constant density level or they are fixed to moorings at a variety of depths for up to two years. Beyond simply assessing particle and carbon fluxes, the Agency has further used sediment traps to evaluate associated fluxes of radionuclides, both of anthropogenic and natural origin

Secondly, information has been gathered based on abundances of natural radionuclides in seawater. Oceanographers have exploited the deficit of the seawater activity of the daughter thorium-234 (^{234}Th), which is particle reactive, relative to that of its parent ^{238}U, which is soluble. In upper waters, where particles are produced, thorium adsorbs onto freshly produced particles and thereby leaves the system as these particles settle. The resulting deficit in ^{234}Th along with its half-life of 24 days, much shorter than its parent, is used to assess its removal from the productive upper ocean. The carbon flux is estimated by converting the ^{234}Th flux and the particulate organic carbon to ^{234}Th ratios as measured in large particles collected in the field with either in situ pumps or sediment traps.

E. Climate change records

E.1. Diagnosing Past Isotope Signatures

Global climate change research has come to rely on radio- and stable-isotope analyses made on natural archives including marine sediments, ice cores, and corals. Stable isotopes are powerful tools because they offer records of past environmental conditions, including temperature, salinity, and pH as well as humidity, biodiversity, and circulation.

For example, oxygen isotope records ($^{18}O/^{16}O$) locked up in the carbonate shells of marine microfossils called foraminifera, or in long-lived corals have been widely used to estimate past temperature, salinity, and circulation regimes, such as the intensity and frequency of past El Niño/Southern Oscillation events as well as related glacial-interglacial changes. Stable carbon isotope records ($^{13}C/^{12}C$) in foraminifera provide constraints on ocean circulation patterns, oceanic nutrient levels, as well as atmospheric CO_2 concentrations. Nitrogen isotopic ratios ($^{15}N/^{14}N$) have been used as a recorder of changes in the productivity and nutrient levels in seawater.

Recently, the advent of the highly sensitive accelerator mass spectrometry (AMS) technique to determine ^{14}C ages on sub-milligram quantities of carbon, e.g. extracted from corals, foraminifera microfossils, marine organic matter, and small volumes of seawater has led to a revolution in our understanding in many process-based aspects of marine science. The demand for AMS analyses of ^{14}C in marine samples has made it a ubiquitous research tool that is now provided as a commercial service in numerous marine laboratories worldwide.

E.2. Radio dating Marine Records

Measurements of isotopes in annual bands from corals has provided sensitive tropical time series of past ocean salinity, temperature, and pH. Seasonal and interannual variations in these isotopic signatures within these annual growth bands have provided reconstructions of El Niño fluctuations over the last 50 years.

E.3. Unravelling Carbon Cycles with Compound-specific Isotope Analysis

Marine isotope chemists have succeeded in miniaturizing and merging conventional carbon isotope techniques into gas chromatography-isotope ratio mass spectrometry (GC-IR-MS) making it possible to analyse carbon isotope ratios in less than a millionth of a gram of organic compound. This will enable scientists, for the first time, to simultaneously identify the sources, pathways and fate of thousands of organic compounds and pollutants found in the marine environment.

For example, microscopic phytoplankton, account for most of living carbon in the ocean, but leave no visual trace following death and burial in sediments. However, they leave molecular fingerprints containing climate-diagnostic isotopes (^{13}C, ^{15}N, ^{18}O). These molecular fossils can now be analysed using GC-IR-MS of sediment extracts. For example, scientists have demonstrated that ^{13}C in alkenone compounds, which are one class of algal compounds out of many that are preserved in sediments, can be used to reconstruct ecosystem structure and temperature in dated marine sediments covering last 300 million years.

Other GC-IR-MS applications include distinguishing terrestrial versus marine inputs of methane plant biomass, and hydrocarbons, and pollutant versus natural origins for many toxic chlorinated organic compounds which accumulate in marine life.

F. Conclusions

This review illustrates a large number of radioactive and stable isotopes that are now being used to trace ocean processes that are important in regulating climate and ocean carbon uptake as well as in evaluating and improving ocean models. New trends in nuclear analytical technologies, as mentioned below, will further enable marine scientists to address key societal and environmental issues such as climate change and ocean acidification.

New Technologies

There is a strong trend towards smaller bench-top analysers and nanoscale technologies, resulting in affordable and portable nuclear and isotopic tools.

Regional Marine Models

There is increasing demand by marine environmental managers for regionally validated marine ecosystems models dealing with erosion, climate risks, blooms and accidental pollution. The numerous natural radiotracers being discovered in coastal marine environments are likely to provide critical insight as these models are evaluated and improved as needed for good sustainable management

Increasing Access and International Links

Ocean and climate studies are by their nature, international and open networks. As such, they provide affordable ways for more Member States to participate and influence the direction of international programmes.

Environmental and anthropogenic isotopes have proven to be sensitive and uniquely informative benchmarks of past and future global environmental change. With instrumental miniaturisation and declining costs, there will be further growth in using marine isotopic techniques to better diagnose the state of the oceans.

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Annex IV
PROGRESS IN DESIGN AND TECHNOLOGY DEVELOPMENT FOR INNOVATIVE SMALL AND MEDIUM SIZED REACTORS

A. Introduction

There is continuing interest in Member States in the development and application of small and medium sized reactors (SMRs). “Small” reactors are defined as those with an equivalent electric power less than 300 MW(e). “Medium sized” reactors are those with an equivalent electric power between 300 and 700 MW(e).

In the near term, most new nuclear power plants (NPPs) are likely to be evolutionary water cooled reactor designs building on proven systems while incorporating technological advances and often taking advantage of economics of scale. Currently such designs range up to 1600 MW(e). For the longer term, there is interest in innovative designs that promise improvements in safety, security, non-proliferation, waste management, resource utilization, economics, product variety (e.g. desalinated seawater, process heat, district heat and hydrogen) and flexibility in siting and fuel cycles. Many innovative reactor designs have been proposed in the small-to-medium sized range. In most cases, they are intended for markets different from those in which large nuclear power plants currently operate, i.e. markets that value more distributed electrical supplies, a better match between supply increments and demand growth, more flexible siting or greater product variety.

B. Current Status: Design and Technology Development

In 2006, more than 50 innovative SMR concepts and designs have been, or are being, developed by national or international programmes involving Argentina, Brazil, China, Croatia, France, India, Indonesia, Italy, Japan, Republic of Korea, Lithuania, Morocco, Russian Federation, South Africa, Turkey, USA, and Vietnam [IV-1, IV-2]. Innovative SMRs are under development for all principal reactor lines and for some non-conventional combinations [IV-2]. The target dates when they would be ready for deployment range from 2010 to 2030. Many of the designs share common design approaches as summarized in the following sections.

B.1. Safety

In SMR designs, as in large reactor designs, defence in depth strategies are used to protect the public and environment from accidental radiation releases [IV-2]. However, nearly all SMR designs seek to strengthen the first and, to the extent possible, subsequent levels of defence by incorporating inherent and passive safety features as well as active safety systems. Certain common characteristics of smaller reactors lend themselves to passive safety features, such as larger reactor surface-to-volume ratios, which facilitate passive decay heat removal and lower core power densities. The first goal is to eliminate or prevent, by design, as many accident initiators and accident consequences as possible. Remaining plausible accident initiators and consequences are then addressed by appropriate combinations of active and passive systems. The intended outcome is greater plant simplicity with higher safety levels that, in turn, might allow reduced emergency requirements off-site.

For innovative water cooled SMRs, design approaches to reduce accident-initiating failures include the integration of steam generators and pressurizers within the reactor pressure vessel. This eliminates large-diameter pipes and large-diameter penetrations in the reactor vessel, thereby eliminating 'large-break' loss of coolant accidents (LOCAs). Figure IV-1 shows the example of the 330 MW(e) SMART design. Some designs also apply in-vessel control rod drives, which both eliminates inadvertent control rod ejections leading to reactivity insertion accidents and reduces the number of reactor vessel penetrations [IV-2]. A second approach to preventing loss of coolant accidents uses compact loop designs with short piping and fewer connections between components. The approach is based on operating experience with submarine reactors. Figure IV-2 shows the example of the KLT-40S design.

All high temperature gas cooled reactor (HTGRs) designs fall in the SMR size range. Figure IV-3 shows the example of the 165 MW(e) pebble bed modular reactor (PBMR). HTGRs use tristructural-isotropic (TRISO) coated fuel particles, each or which consists of a fuel kernel coated with, among other layers, a ceramic layer of SiC that retains fission products at high temperatures. The PBMR design uses graphite spheres (pebbles) in which thousands of TRISO fuel particles are embedded, but other HTGR designs use pin-in-block type fuel with graphite TRISO particles incorporated in graphite pins. The ability of TRISO fuel particles to contain fission products at high temperatures creates additional opportunities, relative to established practices in light water reactors, in designing safety systems and mitigation measures and essentially makes it possible to eliminate adverse consequences of many severe accidents by design. Passive decay heat removal in HTGRs is accomplished by heat conduction through the graphite holding the TRISO particles, followed by

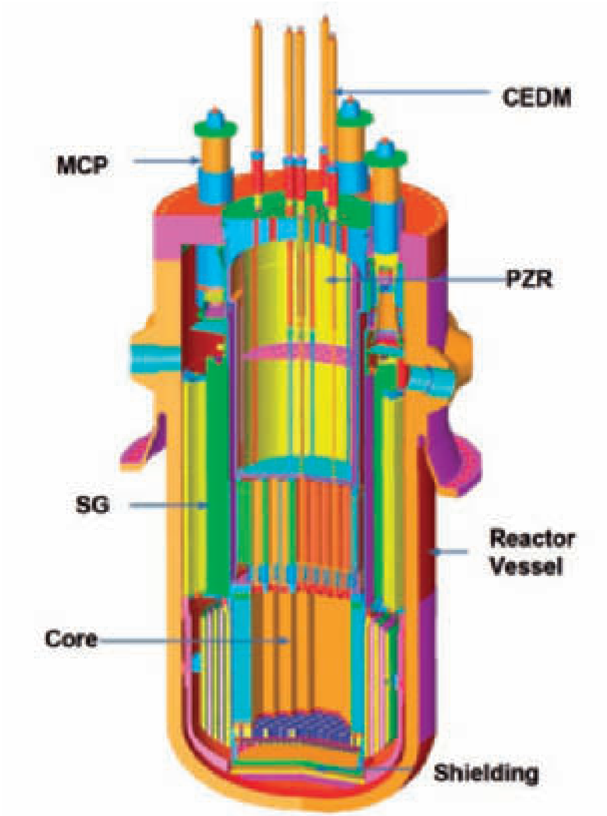

FIG. IV-1. Layout of the SMART integral primary coolant system. MCP = main circulating pump; CEDM = control element drive mechanism; PZR = pressurizer; SG = steam generator. (Source: KAERI-MOST, the Republic of Korea).

convection and radiation in the structures and other media. Also, due to the large heat capacity of the graphite in the HTGR core, HTGRs have a slow and stable response to transients caused by initiating events.

All fast reactor designs in the SMR family offer greater design flexibility in setting desired combinations of reactivity coefficients and effects. This is due to the larger leakage rate of fast neutrons and the high core conversion ratio. The resulting design flexibility creates the potential to eliminate transient overpower accidents by design, to ensure reactor self-control in a variety of other anticipated transients without scram, to enable passive load following capabilities for a plant, and to allow for the power to be controlled solely by adjusting the feedwater flow rate in the steam-turbine circuit [IV-2].

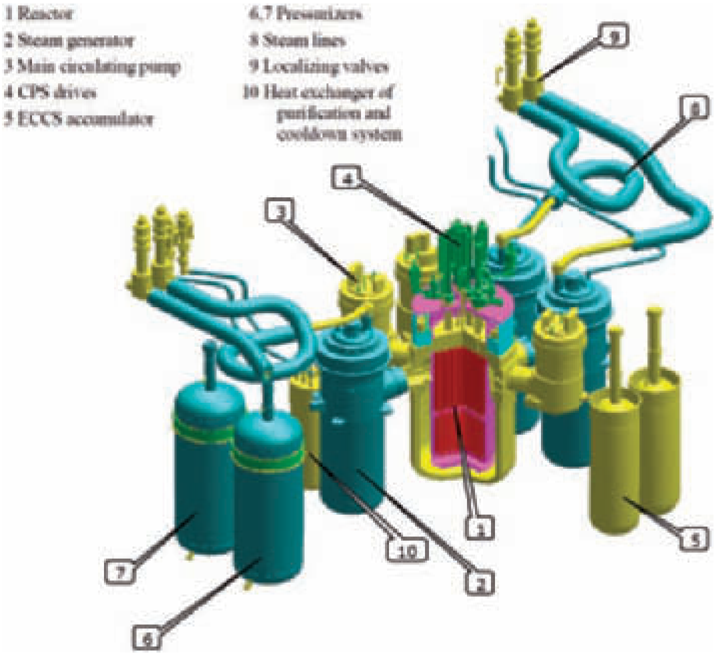

FIG. IV-2. Modular layout of the KLT-40S reactor plant (Source: OKBM, Russian Federation).

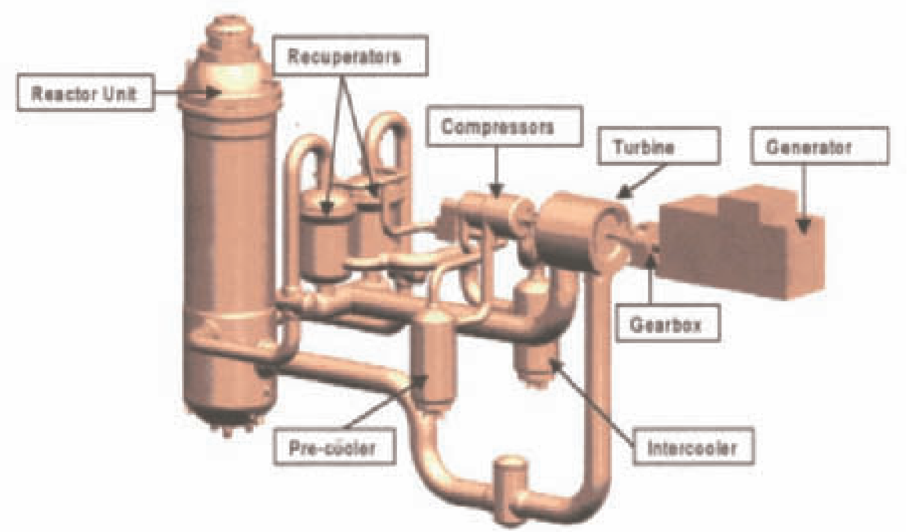

FIG. IV-3. Conceptual layout of the PBMR primary system, offering >41% energy conversion efficiency with direct gas turbine cycle (Source: PBMR Ltd., South Africa).

B.2. Economics

The most common design approaches to improve the economic performance of SMRs are [IV-1, IV-2]:

- to reduce plant complexity and reduce, as much as possible, by design, both accident initiators and their potential consequences;
- to reduce the construction time and cost, to enable a more rapid return on investment, by:
  - sizing the reactor for transportability (or at least transportability of modules) and
  - targeting a standardized design with no site specific modifications;
- to take advantage of cost reductions through factory mass production associated with serial manufacture of standardized plants or equipment modules incorporating unified structures, systems and components; and
- to build into the design the option of cost-saving 'just-in-time' incremental capacity additions and to take advantage of small module sizes to:
  - accelerate learning curve effects and
  - reduce interest costs and investment risks.

In order to facilitate just-in-time incremental capacity additions, design approaches include:

- setting aside space for future incremental additions,
- sizing the switchyard, water and district heat distribution pipelines, etc. for growth,
- sharing railroad, road and sea access facilities among future increment plants, and
- multi-module plant configurations with shared components (see Fig. IV-4).

To reduce operation and maintenance (O&M) costs, SMR designs generally reduce the number of structures, systems and components that require maintenance and, in some case, design for passive load following or autonomous operation. Examples discussed below include small reactors without on-site refuelling: these require neither refuelling equipment nor storage capacity for fresh or spent fuel.

Almost all water cooled SMR concepts use a Rankine steam cycle with saturated or slightly superheated steam for energy conversion. The maximum energy conversion efficiency is approximately 33% based on reactor core

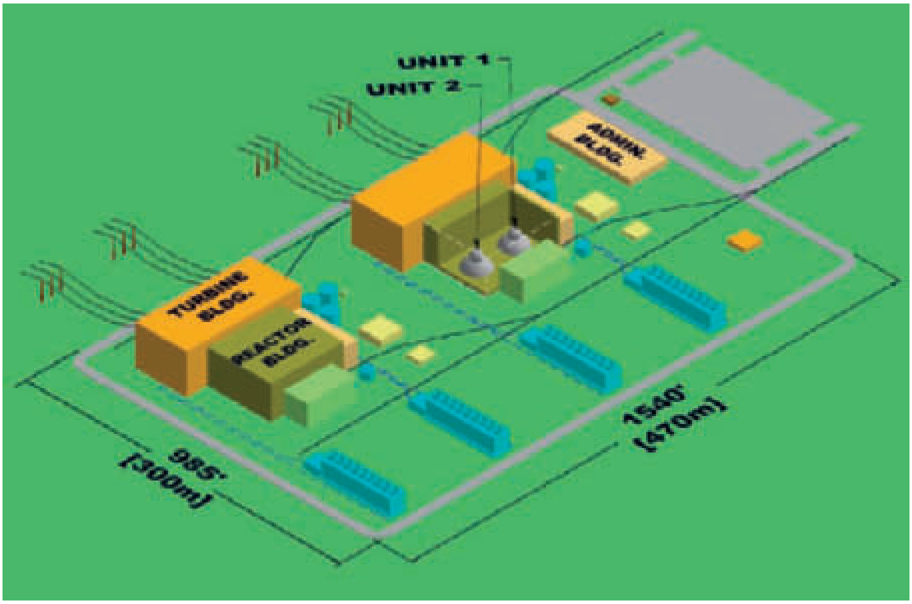

FIG. IV-4. Perspective view of IRIS multiple twin-unit site layout (Source: Westinghouse, USA).

outlet temperatures between 270 and 345°C. In contrast, most HTGRs achieve higher energy conversion efficiencies of 41–50% using direct Brayton cycles or re-using otherwise rejected heat. Several prospective liquid metal cooled, gas cooled and molten-salt cooled SMR designs may also use higher core outlet temperatures and gas turbine Brayton cycles.

Bottoming co-generation cycles, which are incorporated in many SMR designs to produce potable water, district heat or process heat, can, in some cases, recycle heat that would otherwise be rejected to increase overall plant efficiency.

B.3. Proliferation Resistance

Being small or medium sized does not, by itself, make a design more proliferation resistant. Proliferation resistance depends on the incorporation of specific technical features and operational options, coupled with extrinsic features. As with large scale designs, SMR designers seek to include features that impede the diversion or undeclared production of nuclear material, or the misuse of technology [IV-2].

Intrinsic proliferation resistance features common to HTGRs include high fuel burn-up (which leaves a low residual inventory of plutonium, but with a high share of plutonium-240); a fuel matrix that is difficult to reprocess; high radiation barriers; and a low ratio of fissile material to fuel-block/fuel-pebble material. Although several HTGR designs allow for the future possibility of reprocessing TRISO fuel, the technology is not yet established, and until it is, its absence is considered to provide enhanced proliferation resistance. TRISO fuel is also being considered for some innovative water cooled, molten salt cooled and lead-bismuth cooled SMRs. To the extent it is used in such designs, they also would benefit from the proliferation resistant features described here for HTGRs.

Small reactors without on-site refuelling, a category that includes more than half of all innovative SMR concepts, offer additional proliferation resistance features. These are summarized in the general description of such reactors in the section below.

B.4. Small Reactors without On-site Refuelling

Small reactors without on-site refuelling are designed for infrequent replacement of well-contained fuel cassette(s) in a manner that impedes clandestine diversion of nuclear fuel material [IV-1, IV-2]. Figure IV-5 shows the example of Toshiba's 4S design. Such designs aim for refuelling intervals that are much longer than those of today's operating reactors (5–30 years or more), but still achieve design objectives for economics and energy security. Small reactors without on-site refuelling are either factory fabricated and fuelled, or design for whole-core reloads performed at the site by a dedicated service team provided by the vendor, which would bring in its own refuelling equipment and fresh fuel and take away when it leaves both the equipment and the spent fuel.

About 30 concepts for small reactors without on-site refuelling are being developed within national and international programmes in Brazil, India, Indonesia, Japan, Morocco, Russian Federation, Turkey, USA and Vietnam [IV-1, IV-2]. Small reactor designs without on-site refuelling are being considered, for both the near term and the longer term, for water cooled, liquid metal cooled and molten salt cooled reactor lines and some non-conventional fuel/coolant combinations.

For both fast and thermal neutron spectrum concepts, the fuel discharge burn-up and the irradiation of core structures are not intended to exceed standard practices for conventional or anticipated designs. The refuelling interval is extended by decreasing core specific power; power densities in such designs never significantly exceed 100 kW(th)/L and often are much lower. To compensate for excess reactivity and burn-up reactivity loss burnable poisons and active control rods are used in thermal systems and fast systems are

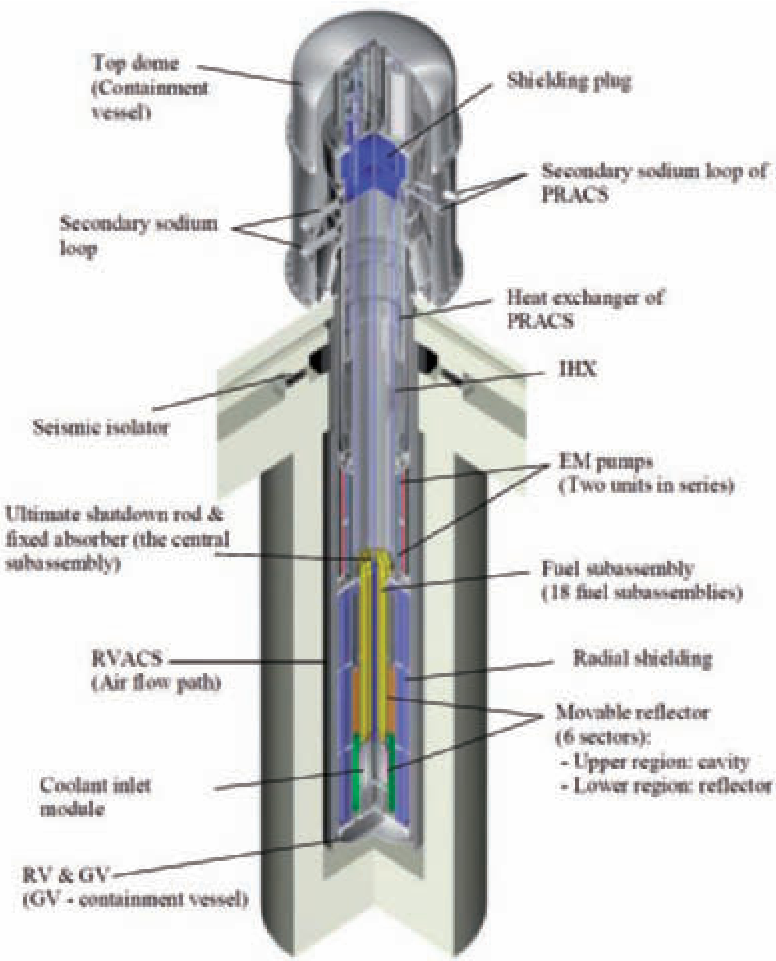

FIG. IV-5. General view of the 4S sodium cooled reactor with a 10–30 year refuelling interval for a 50 MW(e) plant (Toshiba, CRIEPI, Japan).

designed for internal breeding. Although the specific inventories of fissile material (per unit of power and energy produced) are higher than for reactors with conventional refuelling schedules, some concepts for fast reactors without on-site refuelling are capable of self-sustained operation with a breeding ratio of approximately one. This means that the fissile mass in the core is effectively constant throughout its full extended lifetime, while the amount of fertile material decreases and the amount of fission products grows.

C. Opportunities for SMRs

Because SMRs will likely continue to have higher specific costs than large nuclear power plants that benefit from economies of scale, prospects for innovative SMRs depend on their ability to serve several categories of users whose needs are not met by larger plants, such as:

- countries with small and medium sized electricity grids or limited energy demand growth;
- villages, towns and energy intensive industrial sites that are remote from existing grids;
- rapidly growing cities in developing countries with limited investment capability; and
- future merchant plants in liberalized electricity markets, in both developed and developing countries, that might value the reduced investment risk associated with incremental small capacity additions.

The first category includes users in small and medium sized countries where overall targeted energy production is limited, as well as countries with large territories but relatively small and sparse populations.

The second category includes the many areas in the world with remote centres of power consumption unsupportable by electricity grids [IV-4]. Some island countries face a particular challenge in delivering electricity to widely dispersed population centres on scattered islands separated by miles of ocean [IV-5]. Some continental countries include hinterlands with low population densities where grid extension may be not cost effective, or where the cooling water necessary for large plants may be in short supply. The location of many remote settlements is dictated by the location of the natural resources on which they depend, for example, for mining, drilling, logging, fishing, etc. Such remote demand centres may not have sufficient demand for a large nuclear power plant, but may find an SMR cheaper than particularly non-nuclear alternatives with high fuel delivery costs.

The third category is expected to grow, particularly if economic growth in developing countries accelerates in the coming decades [IV-7]. Growing populations, plus increasing urbanization and growing per capita energy use driven by development, may create a market for SMRs because of limited grids in many countries and limited investment capabilities. By 2015, more than 370 cities in Asia, Africa, and Latin America are expected to have more than one million people each; collectively, these cities would account for 1.5–2 billion people. To accommodate rapid demand growth where initial grids and financing are limited, a 'just-in-time' capacity growth plan might be appropriate, with incremental capacity additions as the population grows, as per capita energy use increases, and as a city becomes wealthier. SMRs could meet the needs of these emerging energy markets where the industrial and technical infrastructure is generally poor, if they are designed to be easily expandable into clusters comprising ever-larger power installations.

The fourth category anticipates future situations in which incremental SMR additions matched to demand growth might be attractive to utilities operating in deregulated competitive markets. In these situations, the lower investment risk and shorter payback period associated with SMRs may outweigh their higher capital cost per kilowatt. These advantages may become even more important if nuclear energy broadly enters non-electric markets for seawater desalination, district heating, low temperature process heat, and high temperature heat for, among others things, thermochemical hydrogen production.

Prospects for SMRs also depend partly on how well various SMR designs complement the future evolution of large nuclear power plants. Well over a third of current innovative SMR concepts are fast spectrum nuclear reactors that can achieve high conversion or self-sustainable operation with breeding ratios slightly greater than one [IV-1, IV-2]. Several medium sized concepts go even higher, to breeding ratios of 1.1-1.3. This raises the possibility of breeding fissile materials to feed thermal-spectrum reactors and SMRs fitting well in any transition, at a global or national level, from a once-through to a closed nuclear fuel cycle.

Prospects for SMRs may also depend on the future of current initiatives to limit the global spread of sensitive fuel cycle facilities without constraining the expansion of nuclear power in interested countries [IV-10]. SMRs with long refuelling intervals that are designed specifically to outsource front-end and back-end fuel cycle services, and SMRs without on-site refuelling, could contribute to any of the institutional approaches currently proposed. Some proposals are designed specifically to lessen the risks associated with dependence on outsourced suppliers in a world with continuing political tensions and conflicts between countries (although long refuelling intervals are, in themselves, one way to increase supply security for those outsourcing front-end and back-end fuel cycle services). Such proposals would thus benefit SMR designs that imply a greater dependence on outsourcing. To the extent SMR designs, particularly those without on-site refuelling, are considered more proliferation resistant than alternatives, they will benefit from any incentives developed to favour more proliferation resistant designs. Factory fabricated and fuelled reactors may also be judged more environmentally clean, simple, safe and secure simply because the reactor is effectively a long-life ‘battery’, welded shut and requiring no nuclear fuel handling during its whole operational life at the site.

Potential customers in developing countries are often interested in possibilities for local participation and gradual technology transfer. Nuclear power plants are viewed not only as energy sources but also as vehicles for overall national economic development. Design features responsive to such interests could also contribute to better plant economics, e.g. if certain parts are built to local standards by local firms using local labour and financed in the local currency. However several developing countries, such as Argentina, India and Republic of Korea, are potential sellers of SMRs, with sufficiently mature nuclear industries to offer domestically designed and produced SMRs in the very near term.

D. Challenges for SMRs

Figure IV-6 summarizes the challenges facing SMR development to the extent that some SMR designs may compete directly with large reactors, which benefit from economies of scale. The curve shows schematically the economies of scale (Item 1 in the figure): the greater the size, the lower the specific costs. Items 2-6 summarize factors in SMR design that might contribute to closing the

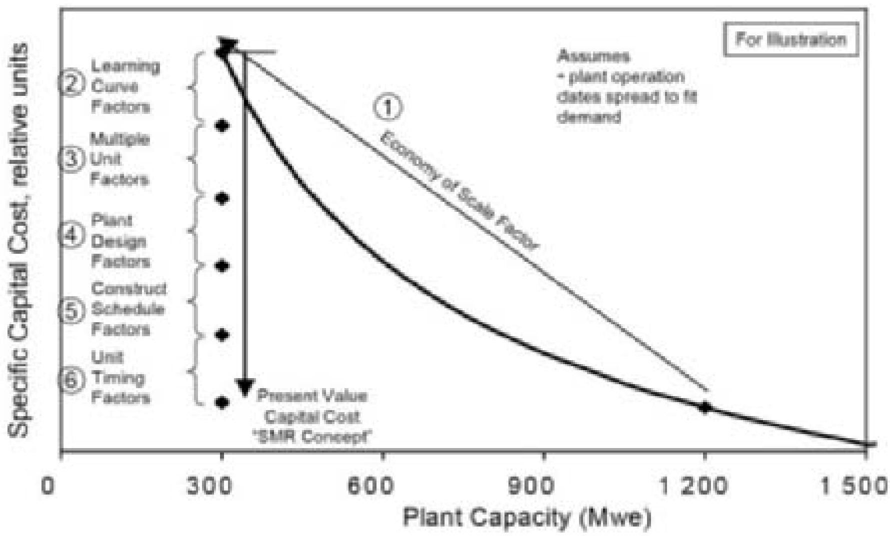

FIG. IV-6. A generic scheme illustrating potential SMR economic factor advantages (courtesy of Westinghouse, USA).

gap between SMRs and large reactors. Although most SMR designs are not intended to compete with large reactors, but with other alternatives in markets for which large reactors are unsuitable, Items 2-6 in Fig. IV-6 still provide a useful conceptual summary of the approaches described above to reduce costs, independent of the intended competition.

In addition to cost reduction challenges, SMR designs face a number of licensing challenges. Many SMR concepts incorporate design approaches and system configurations that do not have proven operating records in the civilian nuclear power sector. Because many innovative SMRs are not water cooled, licensing approaches focussed on current light water reactors may need adjustments toward a more technology-neutral risk-informed approach [IV-1, IV-2]. And some innovative SMR concepts rely on passive systems, the reliability of which needs to be proven to enable risk-informed qualification and licensing.

In addition, many potential applications of SMRs may require them to be located close to customers. Thus an important goal for many SMR designers is a reduction or elimination of a plant's emergency planning zone. This would, again, require a departure from conventional licensing requirements established for LWRs. Examples of such situations include the following.

- In industrial cogeneration applications, such as hydrogen production, SMRs would need to be located near industrial sites if they are to provide process heat.
- SMRs might be sited close to cities that they power in regions where only local electricity grids exist.
- SMRs that produce products such as potable water and district heat, which cannot be transported long distances, would need to be sited near their customers.

Moreover, co-locating a nuclear plant and a chemical plant on a single site would also require new safety rules and regulations to be applied to both.

For small reactors with long core lifetimes and no on-site refuelling, operating experience for such long refuelling intervals is generally unavailable for civilian nuclear power [IV-1], although experience with small marine reactors confirms the possibility of 7-8 years of continuous operation.

Finally, some innovative designs may need validation through testing on prototype reactors, also a lengthy process, to enable series production of a standardized plant.

As SMR designs move forward, and as discussions between possible customers, vendors, governments and regulators continue, the development of common criteria for assessing the suitability of different SMRs in different situations would be useful. Such criteria could be developed using examples of national analyses of the needs for SMRs in member states where the experience with SMRs is positive. They should incorporate all cost components (hardware and services) that are influenced by localization or optimum outsourcing. The criteria could also reflect customer demands for vendor support services (such as licensing issues for innovative NPPs) where there is limited operating experience, operational reliability issues for novel equipment, training of domestic operational personnel, use of local sub-contractors, and other relevant factors.

E. Progress Towards Deployment

For about a dozen innovative SMR designs, current progress in developing the technology and finalizing the design suggests possible deployment within the next decade [IV-1, IV-2]. Construction began in April 2007 in the Russian Federation on a pilot floating cogeneration plant of 400 MW(th)/70 MW(e) with two water cooled KLT-40S reactors. Deployment is scheduled for 2010. In July 2006, the Russian Federation and Kazakhstan created a joint venture to complete design development for a 300 MW(e) VBER-300 reactor (basically a scaled-up version of the KLT-40S) for use in either floating or land-based co-generation plants. They also agreed to promote nuclear power plants using such reactors in both domestic markets and on the global market. Three integral PWR designs are in advanced design stages and commercialization could start around 2015: the 335 MW(e) IRIS design developed by International consortium led by Westinghouse, USA; the 330 MW(e) SMART design developed in the Republic of Korea; and the prototype 27 MW(e) CAREM developed in Argentina, for which construction in scheduled to be complete by 2011. The 165 MW(e) PBMR, developed in South Africa, is scheduled for demonstration at full size by 2012. Additional designs from France, India, Japan and the Russian Federation may also be demonstrated and proven on similar timescales, thus providing several potential choices to interested countries in the intermediate term. In India, licensing and construction activities are scheduled to start in 2008 for an advanced heavy water reactor (AHWR) designed to co-generate 300 MW(e) and 500 m^3/day of potable water. The AHWR is also designed to eventually accommodate Pu-Th and ^{233}U-Th fuel.

In contrast, only a few small reactors without on-site refuelling might be ready for deployment within the next ten years. The only concept that has reached the detailed design stage is the Russian 101.5 MW(e) lead-bismuth cooled SVBR-75/100 with a refuelling interval of 6-9 years. This design benefits from 80 reactor-years of operating experience with reactors of this type in the Russian submarine fleet and is relatively flexible in terms of both applications and fuel cycle options. Russia's Federal Agency for Atomic Energy (Rosatom) is supporting further development for deployment in 2014. The Russian Federation could also develop within a few years, if requested by potential customers, the VBER-150 and KLT-20, which are smaller versions of the KT-40S and VBER-300 respectively, with refuelling intervals of 6 and 8 years. The ABV integral water cooled design is at the basic design stage; it is an 11 MW(e) reactor suitable for a floating nuclear power plant, with a refuelling interval of 8 years.

In Japan, the Toshiba Corporation, in cooperation with the Central Research Institute of Electric Power Industry (CRIEPI) and several other organizations, is developing the 4S sodium cooled reactor. It has a design power of 10-50 MW(e), a refuelling interval of 30 years, and a design that allows the power to be controlled by adjusting the feedwater flow rate in the steam-turbine circuit. The conceptual design and major parts of the system design have been completed. A pre-application review by the US NRC is anticipated in the near future. Construction of a demonstration reactor and safety tests are planned for early next decade.

F. Conclusion

Of the world's 435 nuclear power reactors operating at the end of 2006, 23 were small, 109 were medium sized and 303 were large. Of the 29 reactors under construction four were small, five were medium sized and 20 were large. In the near term, most new nuclear power reactors are likely to be evolutionary large units. But particularly in the event of a shift towards the increasing use of nuclear power in national energy mixes, the nuclear industry can expect an increasing diversity of customers, and thus an increasing number of customers with needs potentially best met by one or more of the innovative SMR designs now under development.

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Annex V
CURRENT TRENDS IN NUCLEAR FUEL FOR POWER REACTORS

A. Introduction

Since 1986 growth in nuclear capacity around the world has averaged 1.5% per year. Growth in nuclear electricity generation has been almost twice as fast, at 2.9% per year (IAEA 1986-2006). Much of that increase is due to improved performance and increased capacity factors of existing plant, which have been aided by, among other things, improvements to the performance and reliability of nuclear fuel.

Nuclear fuel is at the heart of a nuclear reactor, and the safe and economic behaviour of this fuel is a key factor in the continuing long term development of nuclear power. This was recognized early, with the key issues determining the economic drivers for fuel development summarized, for example, in 1977 in Oak Ridge National Laboratory's report, "A Survey of Nuclear Fuel Cycle Economics 1970–1985" (Prince et al. 1977). It was originally anticipated that there would be a first stage involving pool storage of spent fuel, a second stage where reprocessing would lead to the use of plutonium bearing (MOX) fuels in light water reactors and finally the use of fast breeder reactors. The timescales anticipated are now seen to have been extremely optimistic, and the economics are no longer so clearly driving towards reprocessing and fast reactors. However, the drivers of uranium availability and the costs of enrichment, fuel manufacture and waste management that were identified in 1977 are still valid today, and they have ensured continuous development and improvement in nuclear fuel.

B. Nuclear Fuel Types

The vast majority of nuclear fuel used today consists of uranium dioxide pellets contained in a sealed tube of zirconium alloy to make a fuel rod. There are many variations in the way the rods are supported in assemblies or bundles for use in the reactor, and improvements in both the fuel rod and assembly structure have been continuous. Table V-1 lists typical features of the fuel used in power producing reactors today.

TABLE V-1. Fuel Features

Reactor type	Fuel material	Fuel rod cladding[a]	Typical Assembly	Enrichment
AGR	UO_2	Stainless steel	Circular array of pins in graphite sleeve	2 - 4%
BWR	UO_2	Zircaloy-2	Square array	Up to 4.95%
Magnox	U metal	Magnox alloy	-	Natural
RBMK	UO_2	E110, E635	Circular array	Up to 2.8%
PHWR	UO_2	Zircaloy-4	Circular bundle	Natural
PWR	UO_2	Zircaloy-4	Square array	Up to 4.95%
WWER	UO_2	E110, E635	Hexagonal array	Up to 4.95%

[a] Zircaloy-2 and -4 are alloys of zirconium with about 1.5% tin as the main alloying element. Magnox alloy is magnesium with about 1% aluminium or zirconium. Both E110 and E635 are alloys of zirconium with about 1% niobium.

C. Economics

The most important determinant of nuclear power's future is cost competitiveness compared with alternatives. Nuclear power plants have a 'front-loaded' cost structure, i.e. they are expensive to build and comparatively cheap to operate. There is, therefore, a strong economic incentive to maximise the utilisation of the asset. This means fewer unplanned outages and, for plants with batch reloading, longer operational cycles and shorter outages. The load factor of modern nuclear plants with batch reloading is often over 95%, and two year fuel cycles are becoming common. For plants with on-load refuelling capabilities, maximising utilization of the asset has meant longer fuel dwell (i.e. increasing the total time a fuel element spends in the reactor). For all power plants there is also a need to minimize waste arisings due to limited on-site storage facilities and the cost of waste removal and treatment.

For nuclear fuel, this has meant a need to endure longer operational periods and to demonstrate increased reliability. Fuel failure in operation is expensive for an operator, particularly if it limits output or increases outage durations. Fig. V-1 shows how average cycle length, measured as effective full power days (EFPD) has evolved for BWR and PWR plants in the USA.

The cost of nuclear fuel is small compared with the cost of a nuclear power plant. But fuel is still expensive, prompting continuing efforts to increase performance. Increasing the energy obtained from fuel incurs both additional

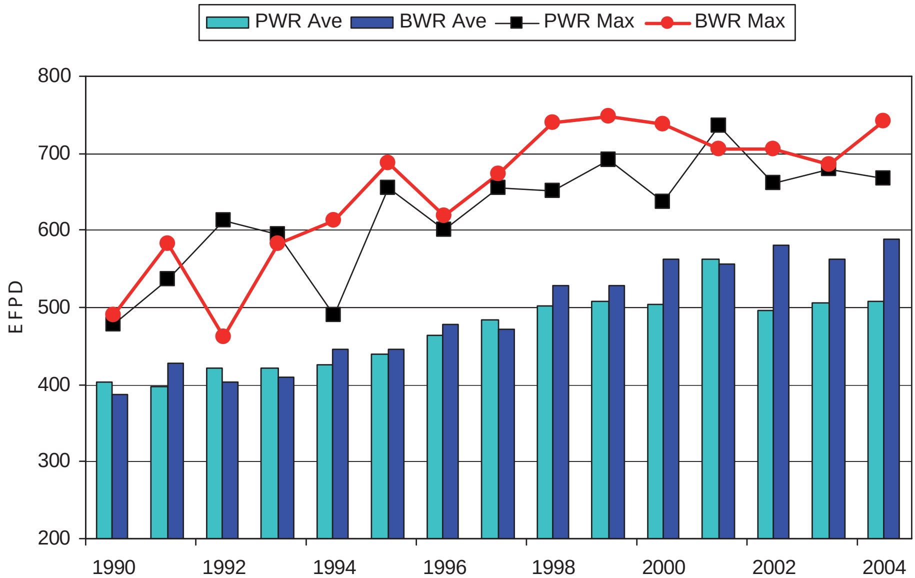

FIG. V-1. Increasing average cycle lengths for fuel elements in PWRs and BWRs in the USA.

costs and savings, with costs coming from the need to add additional enrichment and the management of the high burnup waste material, and savings coming from the need to manufacture and dispose of fewer fuel assemblies. The balance of these costs and savings to date has favoured an increase in fuel burnup, although economic studies suggest that the additional costs for further burnup increases may not be so favourable.

The effect of these drivers has been an increase in the average burnup of the fuel used in all reactor types. The burnup, measured in gigawatts days per tonne of heavy metal (GWd/t U), is a measure of the energy extracted from a given weight of fuel. Figure V-2, which presents the trends of fuel burnup since 1970, shows that the average burnup of light water reactor types has doubled. To achieve this increase in burnup, the main change has been to increase the enrichment of the fuel, typically from 2.5%U-235 to around 4.5%U-235, with a current maximum of 4.95%U-235. Additional changes, as described below, have also been made to fuel materials and their manufacture to ensure reliability over the extended times spent in the reactor.

The increase in burnup has been least marked in the reactor types that use natural uranium as fuel, and whilst the few remaining Magnox reactors are all near final closure, the PHWR vendors and reactor operators are starting to investigate the use of slightly enriched uranium, which will give them the opportunity to double or triple average burnup.

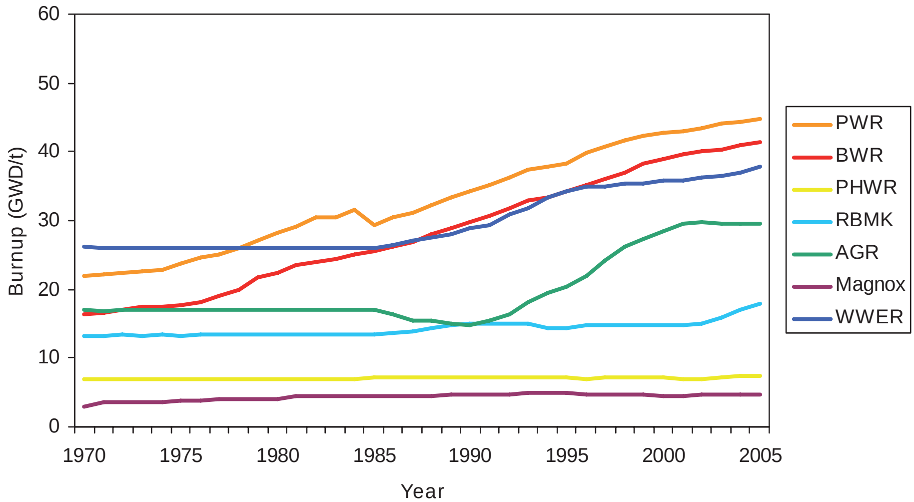

FIG. V-2. Trends in fuel burnup for different types of reactors.

D. Safety

Because nuclear fuel is the source of the vast majority of the radioactivity produced by a nuclear power plant, it is imperative that the design and manufacture of the fuel is sufficiently robust not only to allow it to operate normally without incident, but also to withstand any transient or accident that could occur in the plant in a manner that can ensure that safety is not compromised. This is ensured through a licensing process that oversees, not only operation, but also that the design and manufacture of nuclear fuel is carried out to extremely high standards, and that design requirements are codified and performance is demonstrated experimentally.

In the 1970s there was a large programme of experimental work to demonstrate how fuel would behave under transient and accident conditions, and safety criteria were defined that provided limits on operation such that fuel would not allow an unacceptable release of radioactivity. The intent was that for normal operation and frequent transient conditions, the fuel cladding would not fail, and that under severe accident conditions any fuel failure would be able to be contained and controlled by the plant safety systems. Examples were the testing of fuel under transient high power conditions (power ramps) or under severe loss of coolant accident (LOCA) conditions. As burnup has increased it has been necessary to demonstrate that changes in design or materials do not challenge the limits set by these safety criteria.

The need to demonstrate compliance with the safety requirements means that improvements to fuel design and operation are carefully considered and implemented incrementally, with experimental demonstration, typically through the use of 'lead test assemblies', following extensive testing and research. The incremental approach to burnup extension has been a feature of nuclear fuel development as limitations on burnup extension have been identified and overcome.

E. Modern Design Features

It was noted above that the main change required in nuclear fuel to obtain high burnup is an increase in fuel enrichment, but that alone is not sufficient. Nuclear fuel operates in a demanding environment of high radiation fields, high temperatures and high coolant flow. Early fuel designs were adequate for the initial low burnups, where the time that the fuel was in the reactor was limited, but as burnup has increased it has been necessary to improve the fuel in the many ways, described in this section. All must take into account the fact that material properties change with time under the intense radiation fields in the reactor.

Modern nuclear fuel is the result of a huge investment in research, experimental testing and operational experience. Changes are introduced to improve safety or performance margins or perhaps to overcome a design problem. Some of the more recent challenges faced by fuel designers are described below.

E.1. Clad Oxidation

One of the limits on PWR fuel behaviour is a constraint on the amount of oxide formed on the fuel cladding during operation. A limited amount of oxide is acceptable and even protects the underlying metal from further corrosion. A limit of 100 microns is generally applied, and if the oxide is allowed to grow above this, the protective oxide layer breaks down. This limit is reached with standard zircaloy-4 cladding at an average burnup of around 45GWd/t U, so a programme of clad improvement has been under way for several years. At first, variations in the composition of zircaloy-4 were tried, and increased oxidation resistance was seen with alloys containing less tin as an alloying component. More recently new alloys have been introduced containing 1%Nb as an alloying component, and this has led to a major reduction in oxidation of the cladding during operation, so that the 100 micron limit is not expected to be reached even at the target burnup of 100 GWd/t U.

Introduction of these new alloys is slow, however, and reflects the great care taken in introducing new materials into nuclear fuel. The reasons are due to the necessary testing of the new materials in a reactor. For example, testing new fuel types under transient conditions at extended burnup is necessary to demonstrate acceptable behaviour in abnormal conditions and to define limits to failure. Such tests are very expensive and take many years to carry out. It takes typically six years for a lead test assembly of a new fuel variant to reach the extended burnup necessary before experimental testing can even start.

E.2. Water Chemistry

The relationship between the fuel cladding and water chemistry is very important; changes in the water can profoundly influence fuel oxidation rates and the migration of corrosion products from the steam generators to the fuel, where they can deposit as crud. A consequence of using fuel with higher enrichments and longer cycles is that the distribution of power in a reactor core becomes less uniform, and the local power within an assembly can rise. This has led to deposition of crud from the coolant at high power locations, causing power distortions and even fuel failure through enhanced oxidation. This problem is being addressed by careful core design and control of the water chemistry.

The recommendations for water chemistry have evolved over the years for all water reactor types. An example is indicated in Fig. V-3 for PWRs, where the major events started with the introduction of lithium for pH control in the 1980s, and more recently zinc addition for steam generator corrosion control followed by elevated pH and fuel assembly cleaning to help control crud. The influence of all these changes has to be continually monitored for any effect on fuel performance beyond that intended, a process that takes many years and which accounts for the long lead times before any alterations are widely accepted.

E.3. Assembly Strengthening

Another problem with long residence time in a reactor is that the radiation field can cause elongation of the fuel rods and of the assembly skeleton that holds the rods in place. This elongation is constrained within the reactor, and the assembly has the possibility of bending under the stresses that arise. This ‘assembly bow’ has been observed in both PWR and WWER reactors. The distortion of the assembly can cause local power changes and problems with control rods sticking within the assembly structure. The

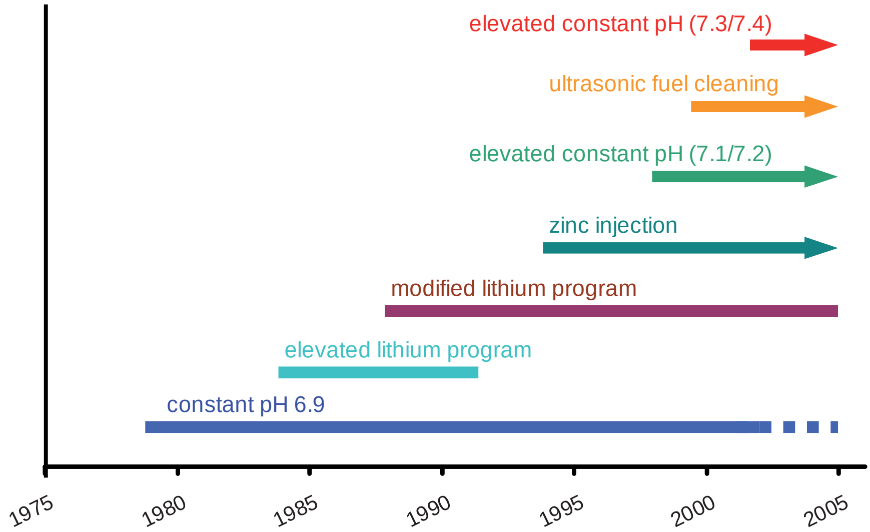

FIG. V-3. Evolution of recommended PWR water chemistry.

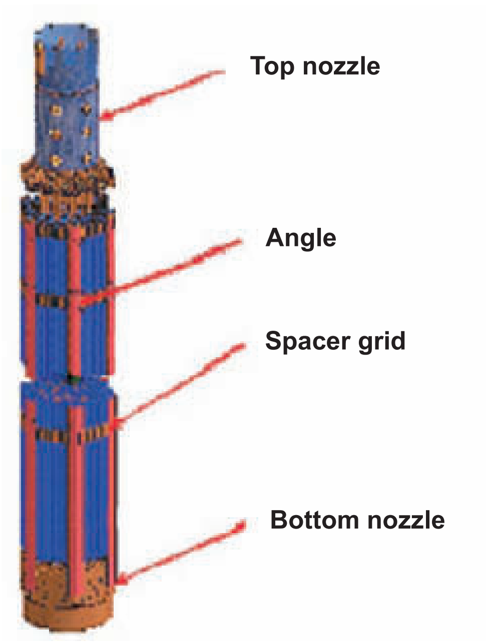

FIG. V-4. Angle stiffening on the advanced TVSA fuel assembly for a WWER-1000 reactor.

response has been to stiffen the assembly, and Fig. V-4 shows the angle stiffening on the advanced TVSA fuel assembly for a WWER 1000 reactor.

E.4. Fission Gas Release

The main problem for fuel designers wishing to increase burnup today is that of fission gas release. Fission gas is generated within the fuel during operation, and the amount is roughly proportional to the burnup. The higher quantity of fission gas is of concern if it is released from the fuel pellet, causing high pressure inside the fuel rod and concerns about clad expansion. There is evidence of increasing release rates of fission gas at high burnups, and many ideas are under investigation to understand and control the phenomenon. Options include adding dopants to the fuel pellet to control microstructure with the aim of reducing the release rate from the fuel during operation and also to increase the resilience of the fuel to power ramps. Currently, WWER fuel pellets have annular geometry, with the central hole providing lower centre temperatures and a free volume to allow any released fission gas to expand and thereby reduce internal pressure. However, WWER fuel designers are considering moving to a solid pellet to allow for a higher fuel load in an assembly and improved utilization, while conversely, PWR fuel designers, who already use a solid pellet, are investigating the use of annular pellets.

New physical phenomena are also becoming evident as fuel pellets achieve higher burnups. A high burnup structure (HBS) with high porosity is seen to develop on the rim of the pellet, affecting fuel temperature distribution as the pellet burnup exceeds 45 GWd/t U. This structure is first seen when fission gas release rates are increasing, but experimental investigations do not confirm that this structure is solely responsible. The actual effect of the HBS on the performance of fuel at higher burnup and also of other potential mechanisms that could cause changes in fission gas release rates are the subject of much research and debate.

E.5. Fuel Failure in Normal Operation

The improvement in fuel failure rates has been a very important trend over the past twenty years. Failure occurs when the cladding is breached, allowing coolant to enter the fuel rod and fission products to escape. A nuclear power plant is designed with appropriate clean up systems so that a few fuel failures do not challenge operation, nor do they generally diminish plant performance. However failed fuel does release radioactivity to the primary coolant circuit, and this can cause additional operator exposure and is an unwanted source term for accident analysis. Power plants have defined limits

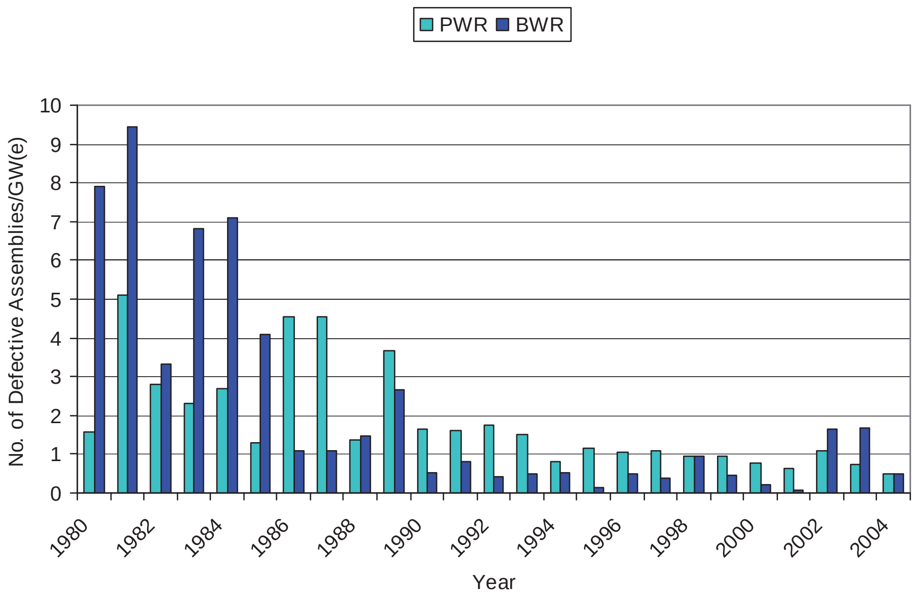

FIG. V-5. Fuel failure rates in US plants.

on the amount of radioactivity that they can tolerate in the circuit, and if sufficient fuel failure occurs it is possible that the plant may have to constrain operation or even shut down to remove the failed fuel. Further, there is general acceptance that reloading failed fuel into a new operational cycle is not acceptable, so expensive search and repair is undertaken when failed fuel is discharged. Systematic efforts have been made to identify and eliminate causes of fuel failure during normal operation and much has been achieved. Fig. V-5 shows fuel failure rate trends in US plants (Yang et al. 2005).

Failure mechanisms that have been identified and remedied include the following. First are manufacturing defects, which are remedied through improved quality assurance methods. Second is grid-rod fretting, which is caused by the grid springs rubbing against fuel rods and wearing through the cladding, and which has been reduced through detailed design changes to assembly grids. Third is debris induced failure, which has been addressed through better plant procedures to avoid debris ingress to the coolant circuit, and also through the introduction of debris filters for the assemblies and protective end caps on fuel rods.

Trend diagrams, such as Figure V-5, are used to spot early signs of a new problem, and attention has been paid to oxide failures in BWRs which have been occurring over the past few years. Fuel vendors are pursuing a goal of ‘zero defects’, and some recently introduced fuel types are very close to this ideal.

E.6. Burnable Poisons and Core Design

To achieve high burnup through the use of higher enrichments, it is necessary to control the additional reactivity of fresh fuel assemblies. To this end, fuel designers include burnable poisons into fuel assemblies. These are materials that absorb neutrons and ensure that the nuclear reaction can be controlled safely. Early designs used discrete components containing boron or other neutron absorbers alongside the fuel rods, but more recently the poison has been added directly to fuel pellets to allow more flexibility and economy in their use. Examples include boron coating of fuel pellets and gadolinia doping. These poisons are designed to deplete (burnout) during irradiation, and the poison loading and depletion rate are optimized to improve fuel utilization.

Further improvements in fuel utilization have also been achieved by careful core design. In batch loading reactors, the location of fresh fuel assemblies and their relationship with partially burnt assemblies in a core will affect the power distribution and neutron economy. Current low leakage core designs are intended to ensure that neutron loss is minimized and that all assemblies reach a burnup on final discharge that is as close to the theoretical maximum as possible.

E.7. Improved Manufacturing

The manufacturers of nuclear fuel are also improving and upgrading their capabilities, and improvements in fuel utilization arise here too. Stricter tolerances on manufacture can be turned to advantage through reduced uncertainties that need to be analysed in a safety submission. Improved fuel utilization is being achieved within advanced gas cooled reactor fuel by small reductions in pellet bore size and cladding wall thickness, within the original specification, but allowing consistently higher uranium loadings and a smaller amount of neutron absorbing material in the core.

E.8. Improved Calculational Routes

It is required to demonstrate that the operation of nuclear fuel is safe, and to do this vendors and utilities employ codes and models to simulate the fuel operation in the reactor. The codes are used to model fuel performance, reactor physics and thermal hydraulics, as well as many other safety related issues. The codes are also subject to continuous improvement and as computing power has increased over the years it has been possible to remove pessimistic assumptions about fuel behaviour and model important phenomena more accurately. For example it has been the practice to calculate fuel pin behaviour using worst case, bounding assumptions on the fuel duty (a concept which combines burnup, fuel rating and other stresses on fuel). No actual rod has ever experienced such worst-case duty, and the resulting calculations have been very conservative. It is now possible with reactor physics codes to accurately follow the actual fuel duty seen by every fuel rod in a core (typically 50 000) and then use fuel performance codes for each rod to find the most onerous operating conditions, and apply suitably conservative assumptions to this rod. These calculations can demonstrate additional margins for safe fuel performance, giving operators and regulators confidence as burnups are increased.

Fuel modelling codes have been developed alongside the physical improvements made to the fuel. The purpose of these codes is to simulate the behaviour of fuel in reactor, and allow predictions of the status of the fuel for use in deign and safety studies. The codes use models of the processes occurring within the fuel as burnup proceeds, considering temperatures, fission gas release and cladding behaviour. The codes are validated against experimental data, and international exercises, such as the IAEA coordinated research project, FUMEX-2, allow access to high burnup experimental data for modelling teams throughout the world. Changes to fuel materials or design pose a challenge to fuel performance codes as new materials may have different burnup dependencies, for example the creep rate of the cladding material or its potential for hardening. Experimental verification of such high burnup properties is difficult and expensive and very time consuming. Current fuel performance codes are generally validated to a rod burn up of around 65 GWd/t U, corresponding to around 60 GWd/t U assembly average.

E.9. Reprocess and Reuse

The early intention of countries undertaking reprocessing of spent nuclear fuel was to try to extract the remaining fissile isotopes (mainly plutonium, but also ^{235}U) and in particular to close the fuel cycle through the use of fast breeder reactors. This development is still well in the future, but there has been utilisation of reprocessed fuel, and nuclear fuel has been manufactured containing plutonium (MOX fuel) and the reprocessed uranium (repU). MOX fuel use is increasing slowly, particularly in France, (Fig. V-6) as there is a need to manage plutonium stocks arising from existing reprocessing contracts, but some countries are ending their use of MOX fuel as existing arrangements expire, and are reverting to a simple storage of spent fuel.

Another approach to the management of spent fuel, and to increasing the energy obtained from such material, is the DUPIC programme to develop fuel for PHWR reactors directly from the spent fuel of LWR plants. The quantity of enriched uranium remaining in spent LWR is potentially appropriate for use in

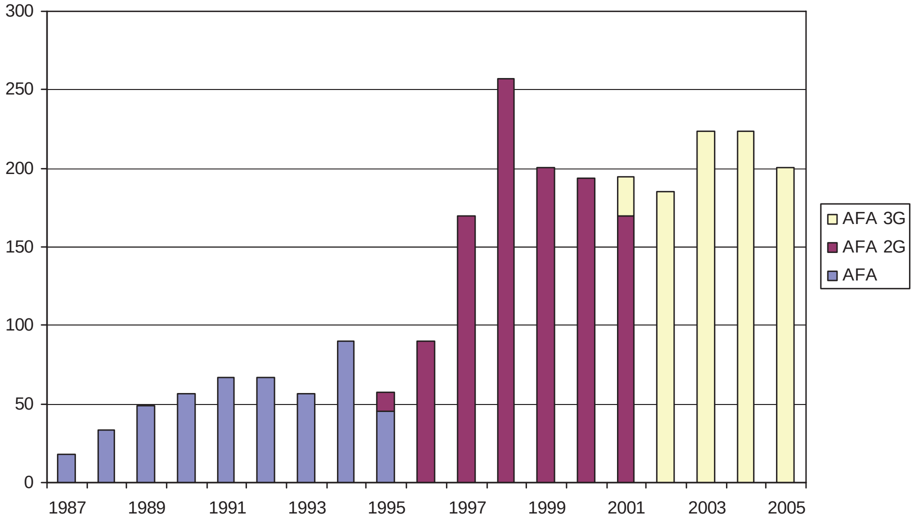

FIG. V-6. Number and type of MOX fuel assemblies loaded in French 900MW PWRs.

a PHWR. The problems of manufacturing the new fuel are daunting, but trials have taken place and this remains a promising development.

F. Future Development

Driving the improvement in fuel performance has been a balance between cost and benefit. Over the past thirty years fuel has become more reliable and the original burnup levels have doubled, with LWR fuel now approaching 60 GWd/t U, thus halving the number of fuel assemblies needed.

Improvements are still possible, previous limitations on fuel endurance, such as cladding oxidation have been overcome by a move to advanced cladding alloys, assemblies have been strengthened to survive longer dwell times without significant distortion and fission gas release has been addressed with advanced fuel pellet technology. It is believed that the current technology could support LWR burnup to even 100 GWd/t U. However, there remain additional costs in reaching these levels, one of which is the need for higher enrichment to go to the higher burnups. All current criticality assessments have been made on the basis of a maximum enrichment level of 5% U-235 and levels in excess of 8% U-235 are needed to reach the 100 GWd/t U target. There is a large investment in fuel manufacturing, transport and on-site handling which has been designed and built for the current enrichment maximum of 5% U-235 and there is currently only one new manufacturing facility that is being designed for a 6% U-235 limit. Experimental work remains to be done on the criticality of such enrichments, and it is likely that further increases in burnup will follow the same slow incremental upward trend that has characterised the past. A second drag on the rapid implementation of new fuel types is the long lead times for irradiation testing to a new burnup level.

One area where new developments are beginning is in the use of slightly enriched uranium fuel for PHWRs. One such reactor, in Argentina, is already using uranium enriched to around 0.9% U-235 and burnups have increased. CANDU operators are looking at higher enrichment levels and considering burnups up to 25 GWd/t U. Once again, the process will be a slow, careful introduction of advanced fuel, combined with improving the calculational tools to ensure predictability of performance and demonstrating experimentally good in-core behaviour.

The nuclear fuel market today is fully commercialized and is a highly competitive one, in which there is currently over-capacity. The vendors are seeking to win orders outside their traditional markets and extending their product ranges to suit different reactor types, a development that is especially noticeable for PWR and WWER vendors. Utilities are using the market and changing vendors when it suits their particular needs. This competition is also forcing the vendors to improve their fuel designs and is another strong force leading to higher reliability and durability. The vendors are attuned to the needs of their customers and to the local conditions in which their customers work. Utilities are now able to pick and choose which fuel enhancement they wish to purchase, which enrichment and burnup target they need, and which cycle length best suits their local electricity market. This is leading to a wide range of customised fuels, and the optimum utilization of a power plant will be tuned to its local market conditions.

G. Conclusions

Nuclear fuel has developed significantly over the past thirty years. Reliability has increased, and fuel pin failure levels are approaching 10^{-6} over the lifetime of the pin. Burnup levels have doubled and issues associated with assembly strength and clad oxidation, among many others, have been addressed. Thermal hydraulics and heat transfer have been improved. Current nuclear fuel technology is capable of fuelling the advanced reactors that are starting to be built, and it is likely that the incremental improvements in fuel burnup, giving optimum utilization, will be the main change over the next decade.

The liberalization of electricity markets in the recent years has seen an increase in competitive pressures in both the overall electricity market and also the nuclear fuel market. This has led — and continues to lead — to a continuous improvement process, with fuel subject to competitive pressure. Vendors will continue to supply the most cost effective solution to a particular utility, whether they wish to use MOX or another advanced fuel type, or whether they prefer a conservative approach utilising only well proven fuel designs.

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Annex VI
SUSTAINABLE DEVELOPMENT: THE ROAD TOWARDS THE 2007 SESSION OF THE COMMISSION ON SUSTAINABLE DEVELOPMENT (CSD-15)

A. Introduction

Some countries argue that nuclear power is fundamentally incompatible with sustainable development. Others argue that nuclear power is essential to their sustainable development strategies. Much of the discussion has taken place within the UN Commission on Sustainable Development (CSD), which in 2006 and 2007 focused on energy for sustainable development, industrial development, air pollution/atmosphere and climate change. Given the frequency with which the phrase 'sustainable development' appears in institutional statements of visions, missions, goals and objectives, a decision by the CSD that nuclear power is inconsistent with sustainable development could constrain nuclear power in unexpected ways.

B. Sustainable Development

Sustainable development was defined in 1987 by the Brundtland Commission, known formally as the World Commission on Environment and Development, as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).

Extensive literature on sustainable development has developed since 1987, generally dividing the concept into three 'pillars': economic, environmental and social. A full review of the literature is beyond the scope of this summary, but the central important features are summarized in this section.

The original Brundtland definition emphasized two points: the importance of economic development (to satisfy needs) and the significance of the natural environment (both as resource provider and waste absorber). The latter is formulated as a social directive for intergenerational linkages rather than as a direct resource use and environmental protection principle. Subsequent elaborations and analyses have converted the simple Brundtland concept into a sophisticated system with three pillars – one each for the economic, environmental, and social aspects of sustainable development (Pearce et al. 1989; World Bank 1992, 2003).

Starting with the economic pillar, there is a broad consensus about the key importance of energy for economic development. The minimum requirement often referred to is to satisfy the energy requirements associated with basic human needs. The requirement to promote development recognizes that the *availability* of abundant energy has supported the process of industrialization in many countries in the past and it will be crucial for the economic take-off of many less developed countries in the future. The price of energy is crucial and has several implications. *Affordable* energy fosters industrial competitiveness on the production side and affordability (an important social aspect of sustainable development) on the consumption side. Yet the efficient allocation of society's scarce resources requires that energy prices reflect energy's full social costs. Distorted energy prices due to general subsidies or ignored external costs lead to careless and wasteful use of energy and suboptimal allocation of resources. Another important requirement for sustainable development is that energy be provided in forms so that it is *convenient* and *comfortable* to use. This fosters the adoption of advanced technologies on the production side and enhances the quality of life on the consumption side.

The next fundamental criteria for energy imply that it is *safe to produce* and *safe to use*. Setting aside the environmental aspects for the moment (which are discussed below), processes from extraction and mobilization to final use in all energy chains involve various sorts of risks to humans and capital assets (e.g. coal mining disasters, refinery accidents, nuclear installation incidents, etc.). The nature and magnitude of these risks and the human and technical possibilities to reduce them vary considerably.

Additional economic criteria for energy provision to support sustainable development include *security* (i.e. that the sources and delivery lines are trustworthy and sufficiently diverse to allow substitutions and rearrangements at low cost if a source or delivery line fails), *reliability* (energy is available without supply discontinuities like closures, shutdowns, or blackouts), *dependability* (the quality of energy is constant and corresponds to prevailing standards (e.g. voltage, calorific value, and chemical composition), and *flexibility* (energy is available when needed and in the quantities needed).

The environmental pillar of sustainable development has two major components in the context of energy: resource depletion on the input side and human health impacts and environmental degradation on the output side. Depletion fears in the 1970s triggered the 'zero-growth' debate about whether, and to what extent, the world's populations, resource use, and economies could grow indefinitely in a finite world. This debate provided the key motivation for establishing the WCED. Subsequently it was recognized that even if non-renewable resources (in the case of energy, this primarily implies fossil energy sources) were available in huge quantities, their environmental and health impacts would require profound changes in many conversion and utilization technologies or direct limitations of their use (Pearce and Turner 1990, Perman et al. 1996).

On the *depletion* side, the broadly accepted *weak sustainability* criterion implies the principle of non-declining total capital to be passed down to future generations (which links to the social pillar in setting a standard for intergenerational equity). This allows the use of non-renewable energy sources as long as that use is compensated for by equivalent increases in man-made, human and social capital. This also links back to the economic pillar because it requires the *efficient use* of non-renewable energy sources, which can be achieved if prices reflect true social costs, including the scarcity rent, and the timely development of inexhaustible sources of energy.

With respect to *environmental degradation*, the ultimate sustainability criterion is to reduce all emissions from energy conversion and use to the level that corresponds to the absorbing capacity of the receiving environmental component (Pearce 1991). Different energy sources and their associated conversion and utilization technologies differ widely in the nature and amount of harmful substances they emit into air, water, and soil and in the other impacts they impose on humans, landscapes, and other components of the biosphere.

The original concern of sustainable development in the social pillar was *intergenerational equity*, i.e. the availability of non-renewable resources and a clean environment to future generations. Over the years, a whole suite of intragenerational equity and other current social concerns have been added. Proponents argue for including in the social pillar diverse matters like poverty alleviation, gender equity, education, participation, transparency, accountability, and many others. Energy contributes to improvements in many of these social components of sustainable development indirectly. The most important sustainable development concerns directly related to energy include *accessibility* (the actual availability of energy), especially access to modern forms of energy, typically distributed via commercial channels, and *affordability* (the ability to pay for the required energy) (UN-Energy 2005). These two factors are the main determinants of energy-related intragenerational equity, i.e. measures of progress in reducing disparities in energy use across different social groups within a country and among nations globally.

C. The Commission on Sustainable Development

Five years after the Brundtland Commission's report, the United Nations Conference on Environment and Development (UNCED) was held in Rio de Janeiro. Among other things, UNCED produced the UN Framework Convention on Climate Change (UNFCCC), the Rio Declaration on Environment and Development and *Agenda 21*. *Agenda 21* is a comprehensive programme of action for sustainable development. It is effectively UNCED's translation of the Brundtland Commission's definition into more specific policy directions. It has 40 chapters on all aspects of sustainable development and covers energy issues, but has no separate chapter dedicated to energy (UNCED 1992).

Agenda 21 called for the creation of a Commission on Sustainable Development (CSD) to ensure effective follow-up of UNCED, enhance international cooperation, and examine progress in the implementation of *Agenda 21* at the local, national, regional and international levels. The CSD was formally created in December 1992 by the UN General Assembly. It was established as a functional commission of the Economic and Social Council and is composed of 53 members elected for terms of three years. Thirteen members are elected from Africa; eleven from Asia; ten from Latin America and the Caribbean; six from Eastern Europe; and thirteen from Western Europe and 'other'. Additional States, United Nations organizations, accredited intergovernmental and non-governmental organizations can attend sessions of the CSD as observers. The CSD meets annually for a period of two to three weeks. The Division for Sustainable Development in the UN Department of Economic and Social Affairs provides support. The CSD reports to the Economic and Social Council and, through it, to the Second Committee of the General Assembly.

The role of the Commission, as a high level forum on sustainable development, now includes:

- Reviewing progress in the implementation of recommendations and commitments contained in *Agenda 21* and the Rio Declaration on Environment and Development.
- Elaborating policy guidance and options for future activities to follow up the Johannesburg Plan of Implementation (JPOI), the final document produced by the 2002 World Summit on Sustainable Development (WSSD)
- Promoting dialogue and building partnerships for sustainable development with governments, the international community and the 'major groups' identified in *Agenda 21* as key actors outside central

governments who have major roles to play in the transition towards sustainable development. The major groups recognized by CSD are women, children and youth, indigenous peoples, non-governmental organizations, local authorities, workers and trade unions, business and industry, scientific and technological communities, and farmers.

Energy was addressed for the first time at the ninth session of the CSD (CSD-9) in 2001. CSD-9's decision on energy (UN 2001) is thus the first dedicated effort by the CSD to further translate the Brundtland Commission's definition of sustainable development into specific policy directions with respect to energy. Nuclear power was a particularly controversial topic during the extensive preparatory process for CSD-9 and at the two-week meeting. The debate between countries that consider nuclear power an essential component of their sustainable development strategies and those that consider nuclear power fundamentally incompatible with sustainable development was long and thorough. It reached two main conclusions:

(1) Countries agreed to disagree on the role of nuclear power in sustainable development. CSD-9's final text observed that some countries view nuclear power as an important contributor to sustainable development and others do not, and summarized briefly the logic of each perspective.
(2) Countries agreed that "The choice of nuclear energy rests with countries."

D. The World Summit on Sustainable Development

The extensive debate at CSD-9 on nuclear power was not repeated the following year at the World Summit on Sustainable Development (WSSD) in Johannesburg. With respect to energy, the WSSD's concluding Johannesburg Plan of Implementation (JPOI) begins with an explicit call to governments, as well as relevant regional and international organizations and other relevant stakeholders, to implement the recommendations and conclusions of CSD-9 (UN 2002). A new feature of the JPOI was the inclusion of a 'positive list' of technologies: renewable energy resources, efficiency improvements, and advanced energy technologies including cleaner fossil fuel technologies. The JPOI calls for a series of actions to promote the widespread availability of clean and affordable energy, specifically the promotion of the technologies on the positive list.

The word 'nuclear' never appears in the JPOI. Upon the adoption of the JPOI, three States took the floor to state for the record that they did not consider nuclear power to be an advanced energy technology and thus they did not consider nuclear power part of the JPOI's positive list of technologies. One State took the floor to state that it did consider nuclear power to be an advanced energy technology and part of the JPOI list. Subsequent to the WSSD, the first CSD document to explicitly address this issue, the Secretary General's report to CSD-14 (next section), does include nuclear power in the category of advanced energy technologies. The report addresses only four topics in its section on "other advanced energy technologies" (i.e. other than advanced clean fossil fuel technologies): nuclear power, fuel cells, hydrogen and the need for increased funding for research and development (UN 2006a).

The JPOI also reaffirmed that the CSD is the high-level forum for sustainable development within the UN system. However, it called on the CSD to focus on a limited number of issues and only undertake negotiations once every two years. This would shift the balance away from annual negotiations of new or more refined objectives and guidelines and more in the direction of reviewing progress, sharing experience, integrating efforts, developing innovative implementation mechanisms, and engaging broader participation in implementation.

In response the CSD now operates on two-year cycles. The first year in each cycle is a 'review session', in which the CSD assesses progress and focuses on sharing experience, coordinating efforts and other implementation issues. The second year in the cycle is a 'policy session', in which the CSD negotiates new policy decisions to guide future efforts.

E. CSD-14

The first CSD cycle following the WSSD, CSD-12 and CSD-13 in 2004 and 2005, addressed water, sanitation and human settlements. The second cycle, CSD-14 and CSD-15 in 2006 and 2007, addressed energy for sustainable development, industrial development, air pollution/atmosphere and climate change.

CSD-14 took place in New York, 1-12 May 2006. As the first meeting in the two-year cycle, CSD-14 was a review session. It was structured to assess progress and advance implementation in the four areas listed above: energy, industrial development, air pollution and climate change. The preparations and programme encouraged participants to identify success stories in the implementation of relevant sections of the JPOI and *Agenda 21*, to share these at CSD-14, to learn from the success stories of others and to forge new partnerships.

The main programme included, among other segments, a three-day high-level ministerial segment with about 50 ministers, a Partnerships Fair, a

Learning Centre, and a full day devoted to progress and implementation issues associated with small island developing states (SIDS). Many SIDS are particularly vulnerable to climate change and unable to afford needed adaptation measures.

In the high-level segment (Fig. VI-1), ministers stressed, with respect to energy, the urgency of concrete actions to increase access to energy by the poor in developing countries, particularly in Africa, and the priority that should be given to poverty eradication in developing countries. Many called for an integrated approach to energy, industrial development, air pollution/atmosphere and climate change as "an action-oriented basis for deliberations at the Commission's fifteenth session" (UN 2006b).

The Partnerships Fair provided a venue for those involved in, or interested in, recognized CSD partnerships to network, identify partners, create synergies among initiatives and learn from each other's experiences. The Learning Centre provided teaching and training at a practical level on the aspects of sustainable development covered by CSD-14, all directed at advancing the implementation of *Agenda 21* and the JPOI.

All presentations and discussions are either summarized or directly accessible through the CSD-14 website: http://www.un.org/esa/sustdev/csd/csd14/csd14.htm. A summary of the Agency's contributions to CSD-14 is available at http://www.iaea.org/OurWork/ST/NE/Pess/CSD-14.shtml. The Agency's brochure for CSD-14, Nuclear Power and Sustainable Development, is available at http://www.iaea.org/OurWork/ST/NE/Pess/index.shtml.

As a review session CSD-14 produced no formal agreed conclusions. The formal record includes instead a chairman's summary, which was discussed and

FIG. VI-1. Former UN Secretary-General Kofi Annan addresses the high level segment of CSD-14.

revised during the second week of the session but never adopted as a consensus view (UN 2006b).

Of the four topics on CSD-14's agenda, energy dominated the discussions, but nuclear power was not extensively discussed. Several delegations mentioned the role of nuclear power in their energy strategies. Others cited concerns about nuclear power. Some of the major groups were more outspoken. Women and NGOs called for a phase-out of nuclear technology. NGOs objected to the IAEA's role in "facilitating the nuclear industry". Children and Youth argued that nuclear power was neither clean nor renewable nor sustainable. The Scientific and Technological Communities were more supportive of nuclear power while noting the need to address waste disposal, safety and proliferation.

F. CSD-15

A one-week Intergovernmental Preparatory Meeting (IPM) was convened in New York in February and March 2007 to prepare for the fifteenth session of the CSD (CSD-15). The objective of the IPM was to bring forward the issues raised during the review year (CSD-14) and help translate and focus them into policies and actions that could be agreed upon at CSD-15.

Based on initial IPM deliberations, a preliminary draft document was distributed by the Chair that sought to articulate areas of potential agreement. Following further discussion, a revised draft was circulated to serve as the starting point for negotiations at CSD-15.

CSD-15 took place in New York from 30 April to 11 May 2007 (Fig. VI-2). A newly revised draft negotiating text, referring to "cleaner and advanced fossil fuel technology", which excludes nuclear power, was distributed during the first week. However, despite intense subsequent negotiations, CSD-15 could not agree on a new negotiated text. Thus the 2001, CSD-9 decision on energy and the 2002 JPOI, as described above, remain the operative CSD texts on energy. The points of disagreement at CSD-15 included the relative emphasis to be given to fossil fuels and renewables, and the possible introduction of new review procedures, voluntary time-bound targets for progress, and new energy standards and labeling. After the session, the CSD secretariat circulated a 'Chair's summary' of CSD-15.

It did not prove possible within CSD-15 to agree new policy decisions to guide future efforts in the areas of energy, industrial development, air pollution/atmosphere and climate change. However, CSD provided opportunities for sharing experiences, forming new partnerships, and replicating and scaling up examples of successful projects. In addition to the formal negotia-

FIG. VI-2. UN Secretary-General Ban Ki-moon addresses the high level segment of CSD-15.

tions, CSD-15 included formal panels and 'dialogues' with UN agencies, the CSD major groups, independent experts and member states.

All presentations and discussions at CSD-15 are either summarized or directly accessible through the CSD-15 web site: http://www.un.org/esa/sustdev/csd/csd15/csd15.htm.

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Annex VII
DEVELOPMENT OF RADIATION RESISTANT REACTOR CORE STRUCTURAL MATERIALS

A. Introduction

The core of a nuclear reactor is where the fuel is located and where nuclear fission reactions take place. The materials used to encase the fuel in fuel rods, to hold fuel rods together in fuel assemblies, and to hold fuel assemblies in place are all considered 'core structural materials', as are the materials used in control rods and core monitoring instruments and their supporting structures. For fusion reactors the core structural materials are the materials of the first wall, blanket and divertor.

The economics of current nuclear power plants is improved through increasing fuel burnups, i.e. the effective time that fuel remains in the reactor core and the amount of energy it generates. Increasing the consumption of fissile material in the fuel element before it is discharged from the reactor means less fuel is required over the reactor's life cycle, which results in lower fuel costs, lower spent fuel storage costs, and less waste for ultimate disposal. There has been a continuous historical increase in fuel burnup from 20–25 GWd/t U in Generation I reactors to 50–60 GWd/t U in today's Generation II and III light water reactors. Design parameters for Generation IV fast reactors call for more than a doubling to ~100–200 GWd/t U (U.S. DOE 2002). Higher burnups place severe performance demands on materials used in reactor fuels, reactor core components, and reactor vessels. A detailed discussion of very high fuel burnups is provided in 'Very High Burn-ups in Light Water Reactors' (NEA 2006) and in Annex IV.

The core structural materials have to retain their functionality to maintain integrity of the fuel rods and fuel assemblies, preventing release of radioactive materials from the fuel to the coolant. To support higher burnups, improved radiation resistant materials need to be developed that can withstand harsher irradiation environments and higher temperatures. A measure of the effect of irradiation on materials is the number of times an atom is displaced from its normal lattice site by atomic collision processes. This is quantified as displacements per atom (dpa) (ANSI 2007). Fig. VII-1 illustrates the required in-service operating environments for core structural materials in various types of reactors. A typical LWR fuel cladding, at a burnup of 40 GWd/t U, will have experienced about 20 dpa, meaning that, on average, each atom is displaced from its site in the crystal lattice 20 times. In future fast reactor systems it is expected that atomic displacement can reach 150–200 dpa, depending on the characteristics of any alloying elements and the neutron spectrum. Precise estimates of radiation damage require complicated computations.

Materials behaviour under irradiation has been studied for more than 50 years, with most experience in the 'thermal reactor materials' area depicted in Fig. VII-1, where core structural materials are subject to temperatures up to 400ºC and damages up to 20 dpa. Some experience has been acquired in the area of 'fast reactor materials', but the high temperature reactor (HTR) area is much less explored.

Materials to be used for Generation IV reactors and future fusion reactors will operate at even higher temperatures, 500–1000ºC, and experience damage up of ~30–100 dpa. The International Thermonuclear Experimental Reactor (ITER) which will shortly begin construction in Cadarache (France) will create new opportunities to experimentally investigate and better understand the factors that may limit the use of structural materials currently used in fusion facilities ('fusion materials' in Fig. VII-1). ITER will have operating temperatures of 100ºC–300ºC and damages of up to 3 dpa from 14 MeV neutrons (ITER 2005). In DEMO (Demonstration Power Plant), the prototype fusion power reactor that will be constructed after ITER, the operating temperatures are expected to be in the range of 500–1000ºC and damage will reach ~150 dpa at the end of five years of full power operation (Maisonnier et al. 2006). As indicated in Fig. VII-1, commercial fusion power reactors are expected to reach even higher damages.

Significant experimental and theoretical progress will be needed to solve the challenges facing the development of advanced reactors and their core structural materials. Progress will require long-term, coordinated, multidisciplinary efforts, with intensive research needed in the study of radiation damage of materials and especially changes of their mechanical and physical properties at high temperature and radiation dose. The following sections describe briefly radiation damage in materials, technological developments, experimental and computational tools, and future challenges. Special emphasis is given to core structural materials exposed to extreme operating conditions.

B. Radiation Damage and Radiation Effects

Given the tight specifications within which a nuclear reactor must operate, it is critical that, throughout the working life of the reactor, structural materials maintain their mechanical properties and dimensional stability within specified tolerances. Incremental changes in materials during steady-state reactor operations must stay within specifications, and all materials must be

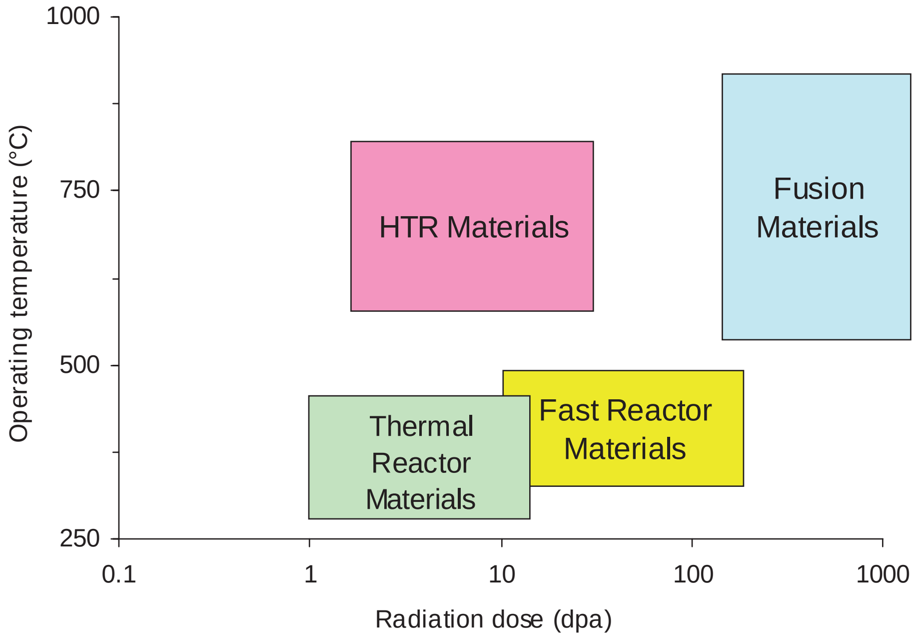

FIG. VII-1. Operating conditions for core structural materials in different power reactors.

able throughout the reactor's life to perform as required under all postulated accident conditions.

B.1. The Basic Nature of Radiation Damage

Radiation induced changes in material properties are the result of microstructural defects. An energetic particle (e.g. neutron or fission fragment) collides with an atom in a material, transferring to it some energy and knocking it out of its lattice position. This primary knock-on atom and the recoiling particle cause additional collisions with other atoms generating a cascade of displaced atoms. Given that the average energy of a fission neutron is ~2 MeV and the threshold energy to displace an atom from its lattice position in metals is ~20–40 eV, a typical number of displaced atoms in a displacement cascade is ~50 000. In most metals, 90–99% of these displaced atoms eventually recombine to vacated lattice positions. It is the remaining non-correctly but stably sited radiation defects and microstructural re-arrangements that constitute the radiation damage that changes the material's microscopic and macroscopic properties. Various types of radiation-induced defects are illustrated in Fig. VII-2.

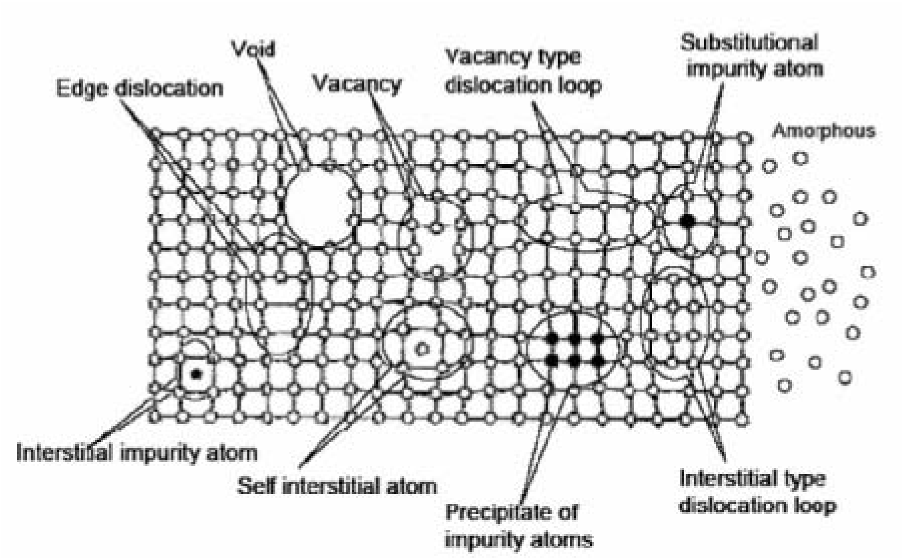

FIG. VII-2. Defects in the lattice structure of materials that can changes their material properties.

Conceptually, these defects can be visualized as regions where there is either a deficiency of lattice atoms (voids, vacancies, edge dislocations, vacancy type dislocation loops) or an excess of lattice atoms (self interstitial atoms, interstitial type dislocation loops). These deficiencies or excesses produce geometrical distortions in the lattice structure. Similarly, impurity atoms (interstitial impurity atoms, precipitates of impurity atoms, substitutional impurity atoms) also distort the lattice structure. All these distortions lead to changes in the mechanical and geometrical properties of the material. For example, vacancies (voids) lead to macroscopic swelling and distortion of the lattice structure, which alters the material's strength and ductility.

The microstructural evolution of a material under irradiation depends on its crystallographic structure. Most metals used in nuclear structural materials have one of three crystallographic structures, two cubic and one hexagonal. Examples of cubic materials are tungsten, iron, vanadium and ferritic steels, which are body centred cubic (BCC), as well as copper, austenitic steels and nickel alloys, which are face centred cubic (FCC). Zirconium and its alloys are the most important 'hexagonal close packed' metals (HCP). A material's crystallographic structure plays an important role in its behaviour under irradiation. Each structure has its advantages and disadvantages and examples of materials used in different core environments and with differing requirements are described in the following sections.

B.2. Macroscopic Effects of Radiation Damage

The most important observable physical changes in material properties are embrittlement, radiation induced growth and swelling, creep, and phase transitions.

- Embrittlement can seriously affect the performance of many reactor components. In materials like BCC ferritic steels, for example, point defects make the material less plastic.
- Radiation induced growth and swelling influence the geometry of core components and can complicate, for example, coolant flow and control rod movements. Swelling is common for FCC austenitic steels and nickel alloys where vacancies tend to form volume clusters. Radiation induced growth in materials such as zirconium, uranium and graphite can lead to different dimensional changes in different directions, depending on the metallographic condition of the material. This is due to an uneven distribution of radiation induced defects forming on different crystallographic planes in their HCP lattice.
- Irradiation creep is a permanent deformation caused by the evolution of different irradiation induced defects, depending on their orientation relative to an applied stress. The material grows in a particular direction and does not return to its original dimensions when the applied stress is removed.
- Phase transitions can be stimulated by irradiation in different ways, leading to negative (and sometimes positive) changes in radiation resistance. Radiation stimulated diffusion of non-equilibrium defects and redistribution of alloy elements may trigger a local transformation of the material's lattice into a more energetically favoured shape. In other cases, irradiation can lead to a homogenization of a multi-phase structure due to atom mixing effects in the displacement cascades.

Fast neutrons can create helium and hydrogen atoms via neutron–α particle (n, α) and neutron–proton (n, p) reactions. These atoms can coalesce into gas bubbles that grow and produce voids and swelling in the material. Additionally, neutron induced transmutations (the change of a natural element due to neutron absorption) can produce significant changes in the elemental composition of materials that adversely affect their properties. Helium embrittlement and transmutations in fusion materials and fast reactors thus exacerbate the degradation of materials from radiation.

B.3. Means to Enhance Radiation Resistance

Given the origins and effects of radiation damage as outlined above, a major focus of current research is on finding ways to stabilize the displaced atoms, vacancies, and lattice distortions. This can be done, for example, by creating features in the material such as grain boundaries or other vacancy sinks to capture and hold migrating radiation defects. Engineering and nucleonic considerations largely determine the major elemental constituents and phase composition of core structural materials, but there remains scope for the adjustment of the micro- and nanostructures of the material to improve radiation resistance. These options include items such as grain size and orientation, trace elements, introduced sinks, and dispersed strengthening precipitates.

C. Nuclear Reactor Materials Development

Resistance to radiation damage, such as dimensional change, embrittlement and creep, is one of the most important considerations in selecting structural materials for a reactor core. More than other components, fuel cladding is exposed to extreme temperatures, pressures, and radiation levels. Consequently cladding material is the most critical in terms of performance and specification design windows. This section thus begins with cladding materials.

C.1. Zirconium Alloys

Zirconium is the most extensively used material for fuel cladding and assembly structure in both light and heavy water-cooled reactors. Its low neutron capture cross-section combined with relatively good corrosion and mechanical properties are among its superior advantages and led to its early use in nuclear reactors in preference to stainless steels. Although high purity zirconium has very good corrosion resistance in water, it has low strength at high temperatures, so alloying is required. Four major alloying elements are used — tin, niobium, iron and chromium — with concentrations of not more than 1.5%. These four elements have very low neutron absorption, so they do not affect the neutron economy of the reactor, but allow the zirconium alloy to meet the required engineering criteria for cladding and assembly components.

The first zirconium alloys developed as structural materials for fuel rods and assemblies in light water reactors were, for U.S. designed BWRs and PWRs, Zircaloy-2 and Zircaloy-4 (with ~1.5% Sn as the main alloying element and no Nb). Russian designed PWRs (WWER) and graphite-moderated pressurized tube type reactors (RBMK) used the E-110 alloy (with ~1 % Nb as the main alloying element and no Sn). The need for suitable materials for different irradiation environments and water chemistries in different reactor designs led to evolutionary developments of such materials in France, Japan, Russia and the USA. These included variations involving small amounts of oxygen (~0.1%), iron (~0.01–0.4%) and chromium (~0.1%), which yielded the current generation of zirconium alloy fuel rod claddings known as M5, MDA, ZIRLO and E-635. In addition, duplex alloys, where an enhanced corrosion resistant outer layer of different alloy composition is applied to a Zircaloy-4 base material, are used in some high burnup applications.

Zirconium and its alloys have a built-in anisotropy (directional dependence) due to their hexagonal close packed (HCP) lattice structure. Such lattice structures can be adversely aligned during material fabrication, resulting in direction dependent irradiation growth leading to cracking. Special thermo-mechanical treatment during tube fabrication aligns the closed packed planes of the lattice parallel to the tube surface, which prevents the radial growth of hydrides from the radiolysis of water and reduces the possibility of radial crack formation and growth and, ultimately, clad cracking. Nonetheless, current understanding of the complex connection between atomistic effects caused by radiation and alterations in observable macroscopic properties is still very limited, and the ability to design, engineer and predict the performance of new materials in high damage radiation environments is still well beyond the present knowledge base.

C.2. Stainless Steels

Although stainless steels are currently used for many core components, the future challenge concerns applications for fuel rod cladding and fuel assembly components in fast reactors that use liquid metals as coolants. Fast reactor components operate at high temperatures (up to 750°C) and neutron irradiations (= 100 dpa), and only special stainless steels can comply with these requirements.

The task of developing fuel cladding materials for a commercial fast reactor able to operate up to burnups of ~200 GWd/t U has not yet been solved. In the extremely demanding design conditions for a commercial fast reactor, both austenitic and ferritic-martensitic steels have limitations — the former due to swelling and the latter due to insufficient high-temperature strength. However, both austenitic and ferritic-martensitic steels allow safe fast reactor operations in power regimes that are at the lower limit of commercial efficiency. Their use in research applications will make it possible to accumulate experience on materials behaviour, and to develop and test new advanced fuels. Currently, the only fast reactor in commercial power operation is the Russian Federation's BN-600, commissioned in 1981. Its fuel cladding is made of austenitic stainless steel (ChS-68) with a ferritic-martensitic stainless steel fuel (EP-450) assembly casing. Increased burnup to ~150 GWd/t U is planned using improved versions of these materials. Related R&D to develop structural materials for fast reactors is also underway in China, France, India, Japan and the USA.

During the past few years, interest has been growing in the development of non-swelling ferritic-martensitic materials with the matrix strengthened by yttrium oxides. This approach is a continuation of an established technique of material strengthening by dispersed fine precipitates. These artificially implanted oxides act as stable obstacles to dislocation movements and reduce creep. Despite the conceptual simplicity of the idea, its technological implementation is difficult.

C.3. Fusion Materials

Fusion power plants will require materials that can withstand high operating temperatures (for efficient thermodynamic cycles), tolerate extremely high displacement damage (for long service lives), and produce low activity by-products (for safe disposal at the end of their useful working lives). Entirely new structural materials will have to be developed for fusion to meet the demanding high-performance requirements, and three major material groups, all of which can fulfil the 'low-activation' requirement, are under investigation: reduced activation ferritic-martensitic steels, vanadium alloys, and silicon carbide composites. Reduced activation ferritic-martensitic steels have so far demonstrated the most potential and are the most advanced in terms of research and development. These steels are the reference structural material for DEMO and will be tested and evaluated in ITER. The requirements for fusion reactors are close to those for Generation IV fission reactors, and materials research activities in the two areas are mutually supportive.

A notable difference between material requirements for Generation IV reactors and fusion reactors is in the amounts of transmutation helium produced by (n, α) reactions. In Generation IV reactors it is projected to reach a maximum of ~3–10 appm (atoms per part per million), whereas in ITER it is ~75 appm and in DEMO ~1500 appm. As previously mentioned, helium induced embrittlement and swelling are major challenges that need to be overcome for the deployment of commercial advanced reactor concepts.

D. Research Facilities for Materials Testing and Investigation

Various micro- and nanoscale experimental and computational tools are required to investigate phenomena in radiation materials science. Experimental techniques are needed to probe elemental compositions, structures, and disordered systems. Nanoscale techniques that have demonstrated their applicability include high resolution transmission electron microscopy, synchrotron radiation techniques and micro-X-ray diffraction, small angle neutron scattering, atom probe tomography, positron annihilation spectroscopy, and muon spin resonance spectrometry. The major facilities required include synchrotron light sources, high-flux research reactors, spallation neutron sources, and high power accelerators.

Research also requires a supply of specimens of suitably damaged materials. Currently there are not enough such specimens because there are not enough facilities where materials can be subjected to sufficiently intense radiation and high damage. For testing potential fusion materials with 14 MeV neutrons, the International Fusion Materials Irradiation Facility (IFMIF) has been proposed (Moeslang et al. 2006). For testing fast reactor materials, there are currently only five operational fast flux reactors available: PHENIX (France), FBTR (India), JOYO (Japan), BOR-60 and BN-600 (both in the Russian Federation) (IAEA 2007). Given the shortage of experimental test facilities, the possibility of using particle accelerators to emulate the neutron damage created by the fission neutron spectrum has been investigated, with encouraging results (Was et al. 2002). However, in-situ experiments done at elevated temperatures and in environments typical of actual operating conditions would still be preferable.

Simulation and modelling of radiation damage also provide new essential insights into the microstructural evolutions that occur during the extremely short period between the initiation and final outcome of the radiation damage cascades. The various steps of collision-recombination-relaxation-defect migration-clustering-nucleation-growth etc. are all essentially completed within periods ranging from picoseconds to milliseconds. Experimentally, it is not possible to observe in real-time these many competing processes. Only afterwards can the resultant static microstructure be investigated in a laboratory. Simulations have already demonstrated their value in radiation materials science using a variety of approaches such as molecular dynamics, kinetic Monte-Carlo, rate theory, and dislocation dynamics (ORNL 2004). But there is still substantial potential for improvement.

E. Current and Emerging Challenges

In the past, it has been possible to test material performance in research and power reactors since the required accumulated radiation damage was relatively small. But with increasing burnup, this approach will not be realistic due to the prohibitively long residence periods and high costs of the required experiments. Existing methods will have to be modified and new approaches developed. One possibility is simulation and modelling to quantitatively predict alterations in material properties, initially at low irradiation doses, following which the models can be refined and validated via experiments (ORNL 2004). Through continuously improving the theory and models to better match experimental results, and through iterations involving increasing irradiation doses, the objective is sufficient reliability and confidence in the model codes to predict the performance of nuclear structural materials in regimes that cannot be realistically achieved experimentally.

Research and power reactors, spallation sources, and accelerators, have all been used to irradiate test materials and study radiation damage. However, despite similarities in radiation damage mechanisms cutting across these different irradiation environments, there are still differences and the same irradiation under different conditions can give different results. Such differences raise as yet unanswered questions about the comparison and evaluation of experimental results in different settings. To help answer such questions, better knowledge of the nature of radiation effects is required through inter-comparison experiments on model materials under controlled irradiation conditions. Well coordinated research projects can make an important contribution, and the IAEA is fostering such cooperative research and development.

Thus while the current level of nuclear materials research and development is adequate to meet the needs of currently operating nuclear facilities, advanced new generation nuclear power plants, both fission and fusion, present major challenges. These are sufficiently substantial in terms of the science, technology, and required resources that no one country or small group of countries will likely be able to maintain the necessary research momentum over an extended period. There is an agreed need for an international mobilisation of resources and internationally coordinated research efforts, probably over many decades. As one immediate contribution, the IAEA facilitates information dissemination and exchange, and promotes collaboration among nuclear institutions, governments, industry, academia, and international organizations.

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