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# Nuclear Technology Review 2007

*Report by the Director General*

## Summary


- In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* each year, which current report highlights notable developments principally in 2006.
- The *Nuclear Technology Review 2007* reviews the following areas: power applications, advanced fission and fusion, atomic and nuclear data, accelerator and research reactor applications, radioisotope applications and radiation technology, nuclear techniques in food and agriculture, human health, and water and the environment. Additional information associated with the *Nuclear Technology Review 2007* is available through www.iaea.org in English on progress in design and technology development for innovative small and medium-sized reactors; trends in nuclear fuel for current types of power reactors; sustainable development: the road towards the 2007 Session of the Commission on Sustainable Development (CSD-15); development of radiation resistant reactor core structural materials; radiopharmaceuticals: production and availability; water use efficiency in agriculture: the role of nuclear and isotopic techniques; and using isotopes to understand the oceans and climate change.
- Information on the IAEA's activities related to nuclear science and technology can also be found in the IAEA's *Annual Report 2006* (GC(51)/5), in particular in the Technology section, and the *Technical Cooperation Report for 2006* (GC/(51)/INF/4).
- The document has been modified to take account, to the extent possible, of specific comments by the Board and other comments received from Member States.

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# Nuclear Technology Review 2007

*Report by the Director General*

# Executive Summary

1. 2006 was a year of 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.

2. 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.

3. 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.

4. 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.

5. 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.

6. 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.

7. 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.

8. 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).

9. 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.

10. 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.

11. 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.

12. 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.

13. 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

14. 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.

15. 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).

16. 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.

17. 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.

18. 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.

19. 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 power plant), 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 |
| 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

20. 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.

21. In 2005, 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.

22. 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 TWh 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 TWh in 2030 (2.6% per year).

23. 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.

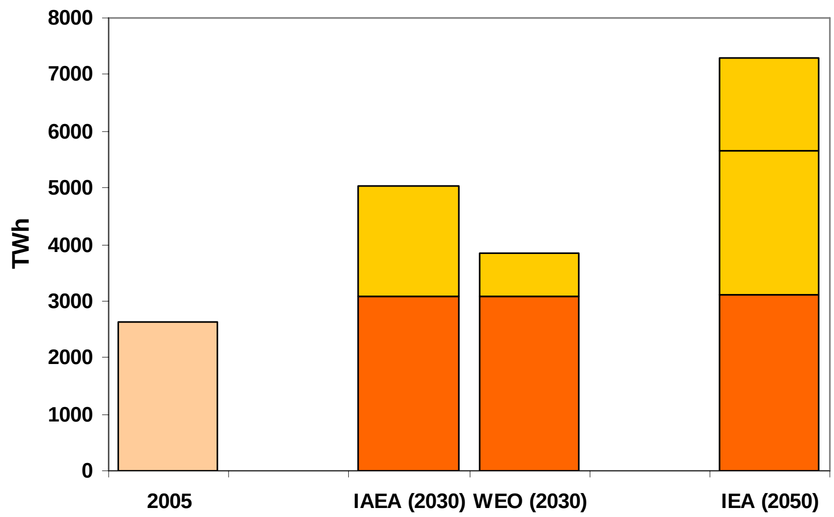


*FIG. A-1. Global nuclear electricity generation in 2005 and the ranges of projections for 2030 and 2050 from three studies (dark orange = low, yellow-orange = high, and beige = history).*

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

[2] IEA, *World Energy Outlook 2006*, IEA, Paris, 2006.

[3] IEA, *Energy Technology Perspectives: Scenarios & Strategies to 2050*, IEA, Paris, 2006.

24. 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.

25. For the IEA scenarios in 2050, on the right side of Figure 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 TWh, or an average growth rate of 1.7% from 2005.

26. 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]

27. 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.

28. The latest estimate of global uranium resources published by the OECD Nuclear Energy Agency (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[6], the table estimates how long conventional uranium resources would last, assuming electricity generation from nuclear power stays at its 2004 level.

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[4] Additional information is available on IAEA.org under "Nuclear Technology Review 2007". 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/).

[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 |

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

30. 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 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.

31. 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

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[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 American power plants.

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]

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

33. 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.

34. 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.

35. 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.

36. 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.

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[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/).

37. 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]

38. 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 paragraph 60). 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.

39. 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 metres. 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.

40. Decommissioning was completed in 2006 at the Big Rock Point nuclear power plant site in the USA, and the site returned to greenfield 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 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]

41. The UN Commission on Sustainable Development's (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 14$^{th}$ and 15$^{th}$ sessions. CSD-14 in 2006 was a 'review session' to analyse the impact of energy policy changes and technological

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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/).

[10] Additional information is available in the related documents to the *Nuclear Technology Review 2007* on IAEA.org. 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.

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.

42. 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.

### A.6.2. Economics

43. 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.

44. 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]

45. 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.

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

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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/.

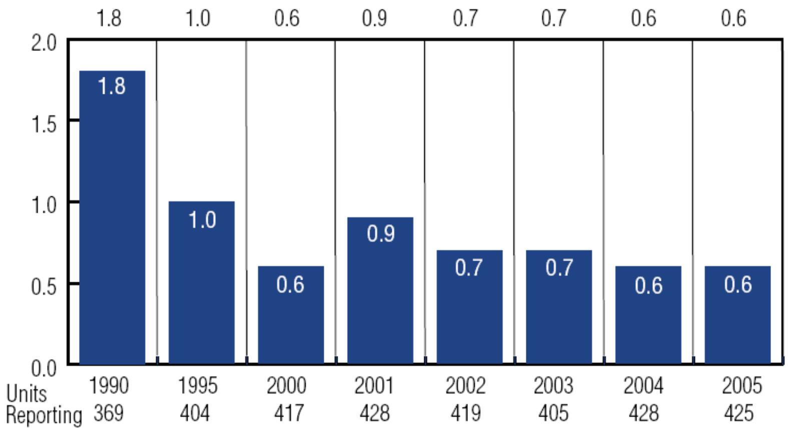


*FIG. A-2. Unplanned scrams per 7000 hours critical. Source: WANO 2005 Performance Indicators.*

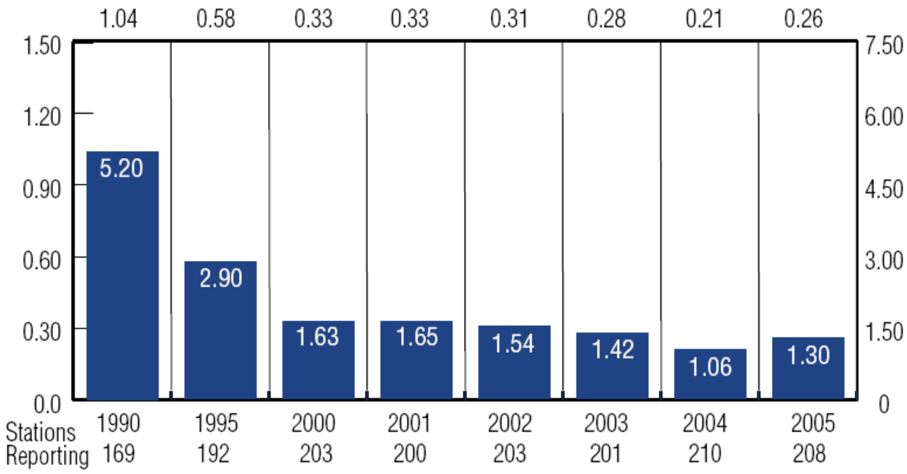


*FIG. A-3. Industrial accidents at nuclear power plants per 200 000 person-hours worked (left scale) and per 1 000 000 person-hours worked (right scale). Source: WANO 2005 Performance Indicators.*

### A.6.4. Proliferation Resistance[12]

47. 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".

[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.

# B. Advanced Fission and Fusion

## B.1. Advanced Fission[13]

### B.1.1. Light Water Reactors

48. 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.

49. 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.

50. 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.

51. 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.

52. 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.

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[13] Additional information is available in the related documents to the *Nuclear Technology Review 2007* on IAEA.org. 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/).

53. 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

54. 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.

55. 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 optimized to use thorium fuel.

### B.1.3. Gas Cooled Reactors

56. 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).

57. 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.

58. 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

59. 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.

60. 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.

61. 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.

62. 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.

63. 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.

64. 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.

65. 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 (ADS)

66. 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.

67. 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.

68. 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.

69. 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

70. 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.

71. The Generation IV International Forum (GIF) grew to thirteen 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 arrangement' 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

72. 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'.

73. 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.

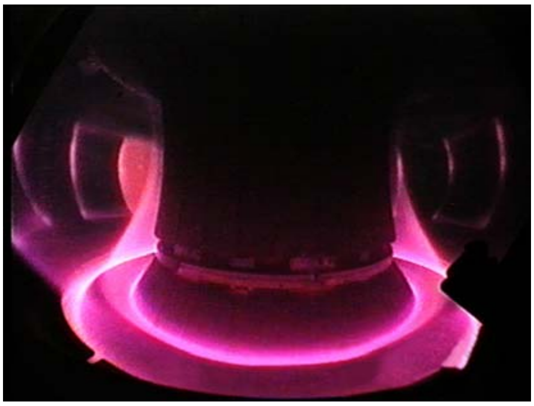

*FIG. B-1. Fusion plasma diagnosis (glowing plasma in the ASDEX Upgrade tokamak, Germany)*

74. 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.

75. Experimental fusion studies are heavily dependent on the ability to monitor and analyse the characteristics of the plasma (Figure 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.

# C. Atomic and Nuclear Data

76. 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.

77. 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 in the quality of various important neutron reaction cross sections are arising as a consequence of comprehensive measurements in the USA and Europe.

78. 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

79. 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

80. 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).

81. 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.

82. 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 multipurpose 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.

83. 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.

84. 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.

**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 & 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**

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

85. The Reduced Enrichment for Research and Test Reactors (RERTR) Programme seeks to convert research reactors using highly 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.

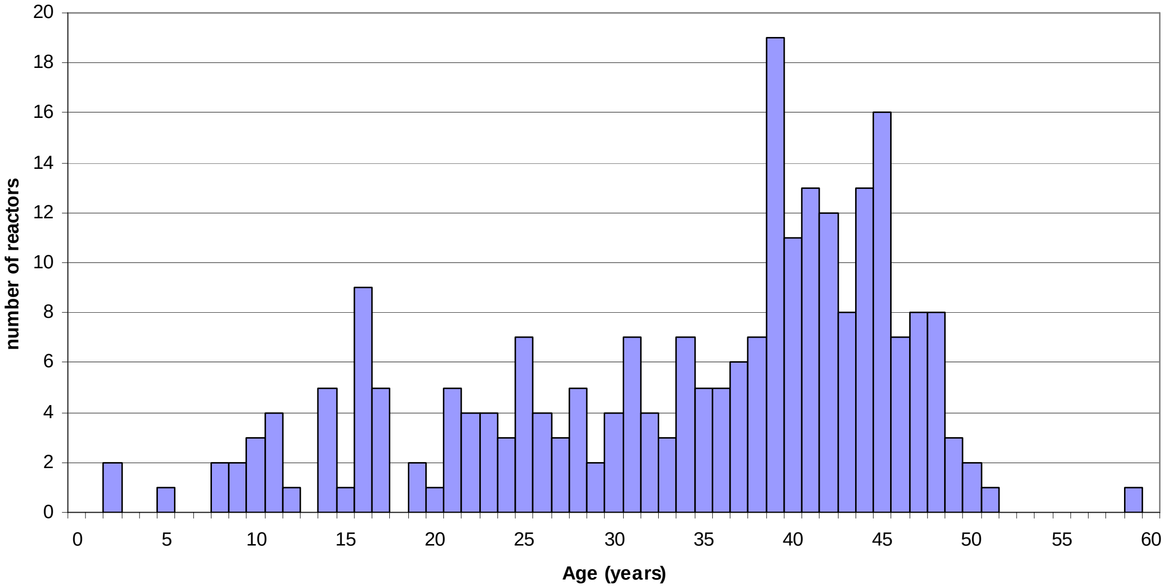


*FIG. D-1. Age distribution of operational research reactors.*

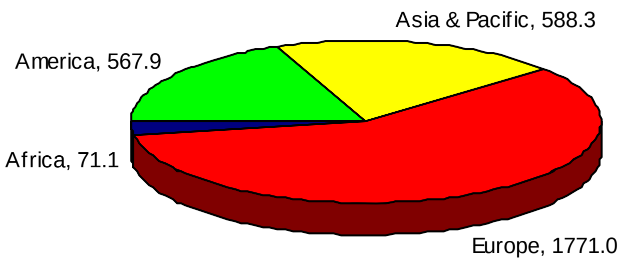


*FIG. D-2.Installed power of operational research reactors in MW (Total = 2 938.2 MW)*

# E. Radioisotope Applications and Radiation Technology

## E.1. Radioisotope Applications in Health[14]

86. 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.

87. 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.

## E.2. Radiation Technology

88. 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

89. 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 below is an example from Japan of the evolution in industrial applications of radiation processing, including grafting of polymers.

[14] Additional information is available in the related documents to the *Nuclear Technology Review 2007* on IAEA.org.

[15] Directory of Cyclotrons used for Radionuclide Production in Member States, 2006, IAEA-DCRP/CD.

**Polymeric adsorbents**

90. 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.

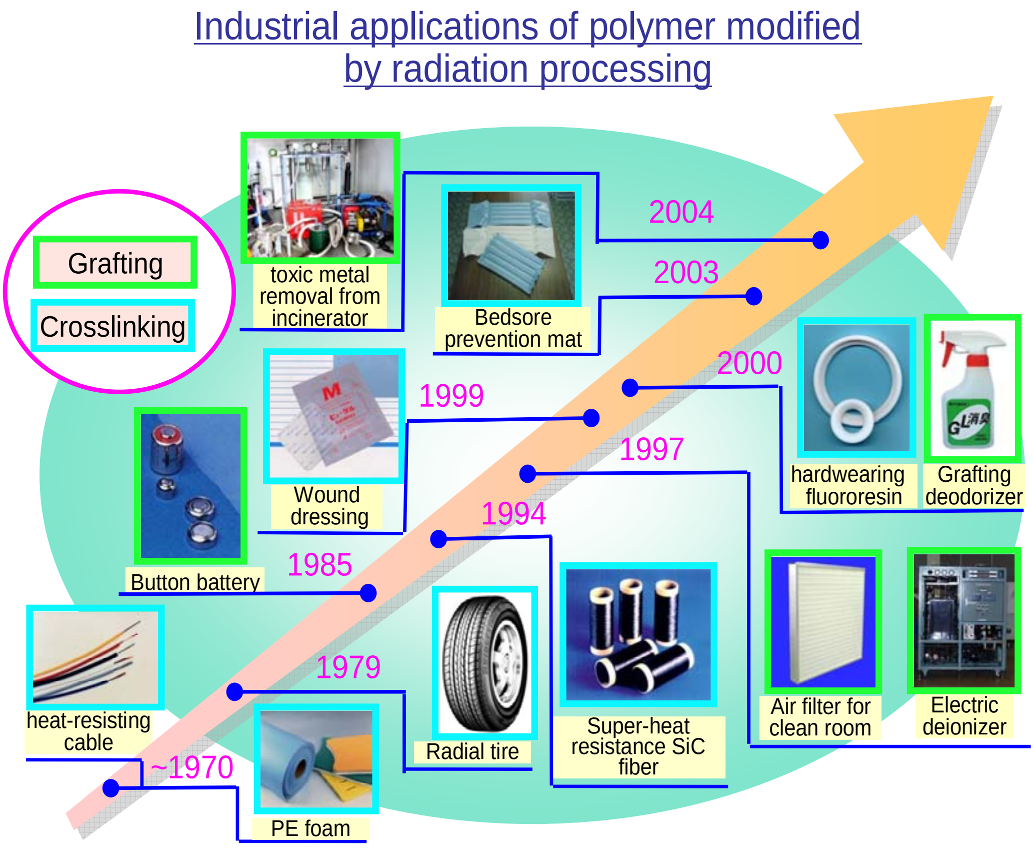


*FIG.E-1: Evolution in industrial applications of radiation processing*

**Polymeric membranes**

91. 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**

92. 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

93. 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.

94. 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.

## F.2. Crop Improvement

95. 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.

96. 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

[16] Additional information is available in the related documents to the *Nuclear Technology Review 2007* on IAEA.org.

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.

97. 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.

98. Radiation hybrid mapping is a technique based on exposing somatic cells to lethal doses of $\gamma$ 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

99. 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.

100. 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

101. 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

102. 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.

103. 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.

*Apple and pear production areas in Patagonia, Argentina.*

104. 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. This 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 Screwworm

105. 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

106. 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

107. 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

108. 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.

109. 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

110. 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.

111. 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.

112. 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 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 Figure 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).

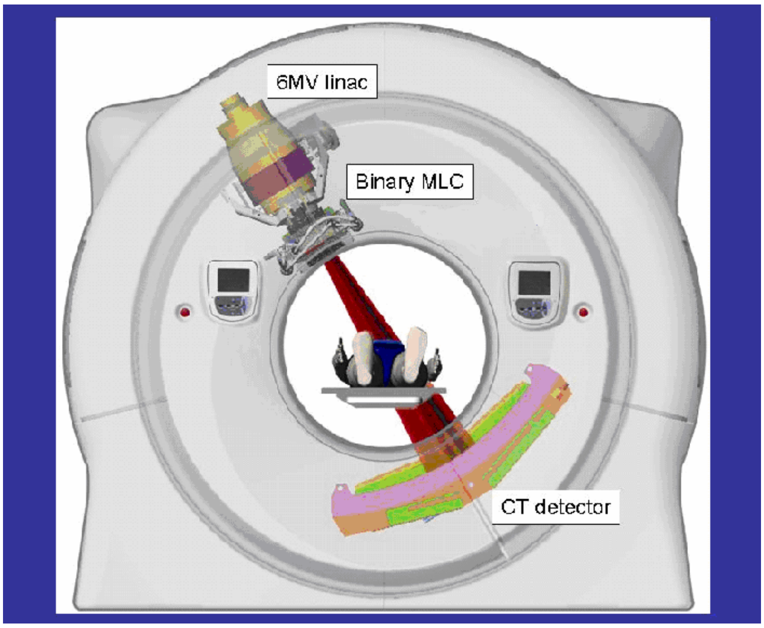


*FIG. G-1. Combined tomography - therapy treatment.*

## G.3. Nutrition

113. 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.

114. 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.

115. 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

116. 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.

117. 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.

118. 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 Figure 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.

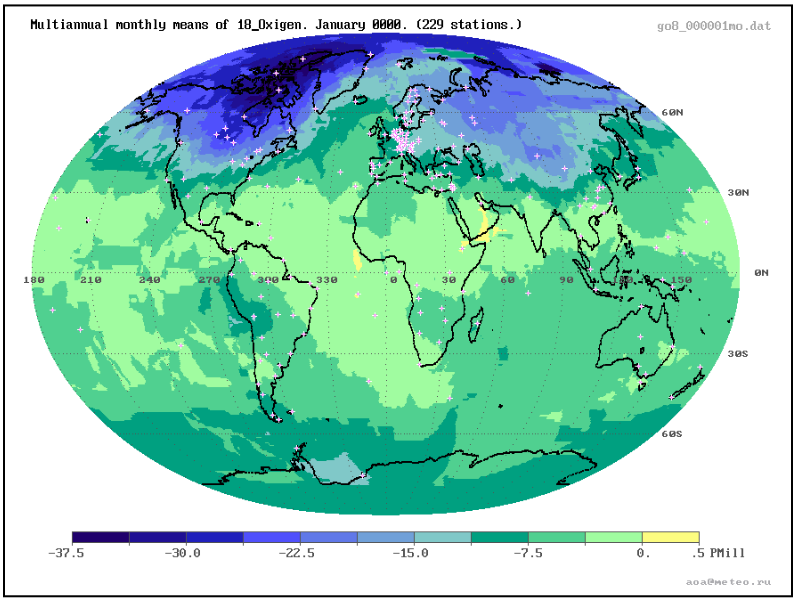


*FIG. H-1. The temperature dependence of isotopes: oxygen isotopes in January.*

## H.2. Marine and Terrestrial Environments

### H.2.1. Microanalysis of Radioactive Particles in Marine Sediments

119. A major fraction of both natural and man-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

120. 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.

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

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[17] Additional information is available in the related documents to the *Nuclear Technology Review 2007* on IAEA.org.

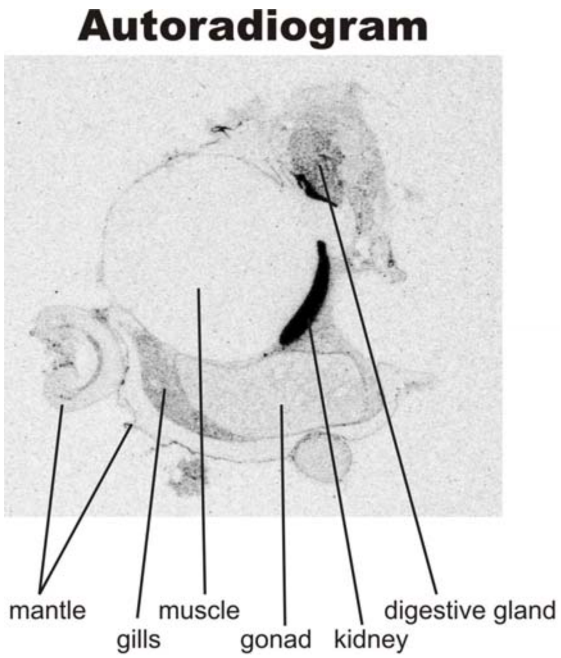


*FIG. H.-2: The black areas indicate the concentrations of the radiotracer cadmium-109 in a scallop (Credit C Rouleau IML Canada)*

## H.3. Air Pollution Monitoring

122. 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

123. 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.

124. 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

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

126. 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 Figure 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.

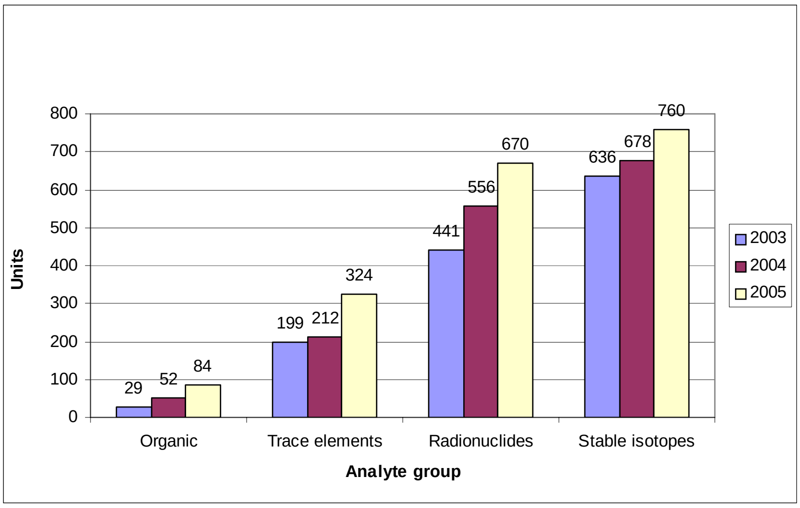


*FIG. H.-4. IAEA reference materials units distributed in 2003, 2004 and 2005.*