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Nuclear Technology Review 2006

Report by the Director General

Summary

- In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* every two years, with shorter updates in the intervening years. This report highlights notable developments principally in 2005.
- The *Nuclear Technology Review 2006* 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 documentation associated with the *Nuclear Technology Review 2006* is available through www.iaea.org in English only on nuclear power in developing countries, storage and disposal of spent fuel and high level radioactive waste, sterile insect technology — research and development, advances in medical radiation imaging for cancer diagnosis and treatment, applications of neutron beam technology and the front end of the uranium fuel cycle.
- Information on the Agency's activities related to nuclear science and technology can also be found in the Agency's *Annual Report 2005* (GC(50)/4), in particular the Technology section, and the *Technical Cooperation Report for 2005* (GC(50)/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 2006

Report by the Director General

Executive Summary

1. While the current outlook for nuclear power remains mixed, 2005 was a year of rising expectations. In March, high-level representatives of 74 governments, including 25 representatives at the ministerial level, gathered in Paris at a conference organized by the Agency to consider the future role of nuclear power. The vast majority of participants affirmed that nuclear power can make a major contribution to meeting energy needs and sustaining the world's development in the 21st century for a large number of both developed and developing countries. Rising expectations are driven by nuclear power's performance record, by growing energy needs around the world coupled with rising oil and natural gas prices, by environmental constraints, by concerns about energy supply security in a number of countries, and by ambitious expansion plans in several countries.

2. There were 441 nuclear power plants (NPPs) in operation as of 31 December 2005 and 27 under construction. Four new NPPs were connected to the grid in 2005 (two in Japan and one each in India and the Republic of Korea), and one laid-up plant was reconnected in Canada. There were two NPP retirements, both in accordance with national nuclear phase-out policies — the Obrigheim reactor in Germany, and Barsebäck-2 in Sweden. There were three construction starts, Lingao-3 in China, Olkiluoto-3 in Finland and Chasnupp-2 in Pakistan. Olkiluoto-3 is the first new construction in Western Europe since 1991. Asia remains the centre of expansion, accounting for 16 of the 27 reactors under construction at the end of 2005, and for 24 of the last 34 reactors to have been connected to the grid.

3. Uranium prices, which had been low and stable for the previous decade and a half, continued their climb — from $25/kg in 2002 to $112/kg in May 2006. Uranium production has been well below consumption for about 15 years, and the current price increase reflects the growing perception that secondary sources, which have covered the difference, are becoming exhausted.

4. As of the end of 2005, eight power plants had been completely decommissioned, with the sites released for unconditional use. Seventeen had been partially dismantled and safely enclosed, 31 were being dismantled prior to eventual site release, and 30 were undergoing minimum dismantling prior to long-term enclosure.

5. Progress on disposal facilities for high level waste is most advanced in Finland, Sweden and the USA. In Finland, construction started in 2004 on an underground characterization facility for the final repository at Olkiluoto. In 2005 Hungary and the Republic of Korea selected sites for their first repositories for low level and intermediate level radioactive waste, following favourable referenda in the communities chosen, and in Belgium two communities voted to become candidate sites for a low level waste repository.

6. National research on advanced reactor designs continues for all reactor categories — water cooled, gas cooled, liquid metal cooled, and hybrid systems. Five members of the Generation IV International Forum (GIF) signed a framework agreement on international collaboration in research and development on Generation IV nuclear energy systems in February 2005. The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) grew to 24 members, with the addition in 2005 of Ukraine and the United States of America. Current INPRO activities include completion of a user manual on the INPRO methodology, application of the methodology to assessing innovative nuclear energy systems (INSs) in national and multinational studies, analyses of the role and structure of INSs in meeting energy demands in a sustainable manner, and selection of the most suitable areas for collaborative development.

7. A major advance in fusion energy occurred in June 2005 with the signing of the joint declaration of all parties to the negotiations on the International Thermonuclear Experimental Reactor (ITER) and the agreement to start construction at Cadarache, France. This decision signalled an important new stage in the development of fusion energy — the scientific and engineering demonstration of fusion technology in conditions relevant to operating a fusion reactor for power production.

8. Both for power generation and all other applications of nuclear energy, progress and improvements are underpinned by continuing basic nuclear research. The realisation of fusion as a viable energy source requires research in many areas, together with reliable atomic and nuclear data. Research reactor applications support most areas of nuclear technology, and uses of new research reactors, for example in isotope production, neutron beam utilization and activation analyses for environment and food and agriculture, are reported in this review.

9. Developments in accelerator based techniques, production of radioisotopes and some novel uses of nanotechnology are also reported.

10. Nuclear technologies continue to play key and often unique roles in food production and safety, in human and animal health, in water resource management and in the environment. Mutation breeding of crops, for example, has led to the use of previously unusable land in many countries for rice production. In human health, the use of stable isotopes is becoming an accepted tool for the development of nutrition programmes. Nuclear medicine is benefiting from technological advances in computing. Sustainable water management and desalination remain high on the international agenda. New developments in isotopic analysis of hydrological samples hold promise for increasing the use of isotopes in water resources management. Advances in sampling and analytical techniques have assisted in better understanding of the environment. Developments in all these areas are also reported.

A. POWER APPLICATIONS

A.1. Nuclear Power Today[1]

11. Worldwide there were 441 nuclear power plants (NPPs) operating at the end of 2005, totalling 368 GW(e) of generating capacity, and supplying about 16% of the world's electricity. This percentage has been roughly stable since 1986, indicating that nuclear power has grown at the same rate as total global electricity for 19 years.

12. Four new NPPs were connected to the grid in 2005 (two in Japan and one each in India and the Republic of Korea), and one laid-up plant was reconnected in Canada. This compares to five new grid connections (and one reconnection) in 2004 and two new grid connections (and two reconnections) in 2003. There were two NPP retirements in 2005, compared to five retirements in 2004 and six in 2003. The net increase in global nuclear generating capacity during 2005 was 3259 MW(e).

13. Using the Agency's definition that construction begins with the first pouring of concrete, there were three construction starts in 2005: Lingao-3 in China (1000 MW(e)), Olkiluoto-3 in Finland (1600 MW(e)) and Chasnupp-2 in Pakistan (300 MW(e)). In addition, active construction resumed at two NPPs in Bulgaria, whose previous classification had been 'construction suspended'. In 2004 there were two construction starts plus the resumption of active construction at two NPPs in the Russian Federation. There had been one construction start in 2003.

14. Current expansion, as well as near-term and long-term growth prospects, are centred in Asia. As shown in Table A-1, of 27 reactors under construction worldwide at the end of 2005, 16 were in Asia. Twenty-four of the last 34 reactors to have been connected to the grid were in Asia.

15. Japan has the largest nuclear power programme in Asia. With the connection of Higashi Dori-1 to the grid in March, and Shika-2 in July, Japan now has 55 reactors in operation and one under construction. Also in July the Tokyo Electric Power Company (TEPCO) returned to service the last of the 17 reactors shut down in 2002. Altogether Japan plans to add ten units to the grid by 2014, increasing nuclear power's share of Japanese electricity to more than 40%.

16. With the connection of Ulchin-6 to the grid in January, the Republic of Korea has 20 units in operation. Site preparations began in 2005 for Kori-5 and -6. Nuclear power provides 45% of the country's electricity.

17. Elsewhere in Asia, nuclear power's absolute and relative contributions are smaller, but China and India in particular plan significant expansion. China, with nine operating reactors, three under construction and 2% of its electricity from nuclear power, plans expansion to 40 GW(e) by 2020 for 4% of the electricity supply.

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[1] The IAEA maintains data on operating and shutdown reactors, and those under construction, as described in the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/nuclear_power.pdf*) and on the IAEA website at *http://www.iaea.org/OurWork/ST/NE/NENP/NPES/index.html*. See in particular, the Power Reactor Information System (*http://www.iaea.org/programmes/a2/index.html*).

Table A-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 31 December 2005)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2005		Total Operating Experience through 2005	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	6.4	6.9	54	7
ARMENIA	1	376			2.5	42.7	38	3
BELGIUM	7	5 824			45.3	55.6	205	7
BRAZIL	2	1 901			9.9	2.4	29	3
BULGARIA	4	2 722	2	1 906	17.3	44.1	137	3
CANADA	18	12 599			86.8	14.6	442	8
CHINA	9	6 572	3	3 000	50.3	2.0	56	11
CZECH REPUBLIC	6	3 368			23.3	30.5	86	10
FINLAND	4	2 676	1	1 600	22.3	32.9	107	4
FRANCE	59	63 363			430.9	78.5	1 464	2
GERMANY	17	20 339			154.6	31.0	683	5
HUNGARY	4	1 755			13.0	37.2	82	2
INDIA	15	3 040	8	3 602	15.7	2.8	252	0
IRAN, ISLAMIC REPUBLIC OF			1	915				
JAPAN	55	47 593	1	866	280.7	29.3	1 221	3
KOREA, REPUBLIC OF	20	16 810			139.3	44.7	259	8
LITHUANIA	1	1 185			10.3	69.6	39	6
MEXICO	2	1 310			10.8	5.0	27	11
NETHERLANDS	1	449			3.8	3.9	61	0
PAKISTAN	2	425	1	300	2.4	2.8	39	10
ROMANIA	1	655	1	655	5.1	8.6	9	6
RUSSIAN FEDERATION	31	21 743	4	3 775	137.3	15.8	870	4
SLOVAKIA	6	2 442			16.3	56.1	112	6
SLOVENIA	1	656			5.6	42.4	24	3
SOUTH AFRICA	2	1 800			12.2	5.5	42	3
SPAIN	9	7 588			54.7	19.6	237	2
SWEDEN	10	8 910			69.5	44.9	332	6
SWITZERLAND	5	3 220			22.1	32.1	153	10
UKRAINE	15	13 107	2	1 900	83.3	48.5	308	6
UNITED KINGDOM	23	11 852			75.2	19.9	1 377	8
UNITED STATES OF AMERICA	103	98 145			780.5	19.3	3 087	6
Total[b]	441	368 264	27	21 811	2625.9	16%	11 991	8

a. Data are from the IAEA'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, 4904 MW(e) in operation; 2 units, 2600 MW(e) under construction;

— 38.4 TW·h of nuclear electricity generation, representing 20.3% of the total electricity generated in 2005;

— 146 years, 1 month of total operating experience.

18. India connected Tarapur-4, a 490 MW(e) pressurized heavy water reactor, to the grid in June. The country now has 15 reactors in operation and eight more under construction. In 2004 nuclear power provided 2.8% of the electricity supply. India's goals are to increase nuclear capacity by a factor of ten by 2022 and a factor of 90 by 2052.

19. Pakistan gets 2.8% of its electricity from two operating nuclear reactors. In 2005 construction began on Chasnupp-2, a 300 MW(e) pressurized water reactor. Plans call for an additional 8000 MW(e) of nuclear capacity by 2030, thereby increasing nuclear power's share of electricity to 4.2%.

20. The Islamic Republic of Iran, which is constructing a nuclear power plant, signed fuel-supply agreements in 2005 that provide for the return of spent fuel to the Russian Federation.

21. Western Europe has 135 operating NPPs and now one under construction with the August 2005 construction start at Olkiluoto-3 in Finland. In line with nuclear phase-out policies in Germany and Sweden there were two retirements, Obrigheim in Germany and Barsebäck-2 in Sweden. Governments approved a lifetime extension of the Borssele NPP to 2033, i.e. a 60-year lifetime, in the Netherlands and ten-year lifetime extensions to Dungeness-B1 and Dungeness-B2 in the UK. The Swedish Government approved uprates of 15 MW(e) for Ringhals-1 and -3, and a similar request for a 250 MW(e) uprate at Oskarshamn-3 has been supported by regulators and is awaiting government approval. Additional uprate requests were for 120 MW(e) at Forsmark-1, 120 MW(e) at Forsmark-2 and 170 MW(e) at Forsmark-3.

22. Russia has 31 nuclear power plants in operation and four under construction, and Eastern Europe has 39 operating plants and five under construction. Bilibino-2 in Russia received a five-year licence extension at the beginning of 2005, complementing a similar extension granted to Bilibino-1 the previous year. Both are small 11 MW(e) units providing district heat and electricity in the remote north-eastern Chukotka region.

23. In the United States of America, the Nuclear Regulatory Commission (NRC) approved nine more licence renewals of 20 years each (for a total licensed life of 60 years for each NPP), bringing the total number of approved licence renewals at the end of 2005 to 39. New energy legislation was enacted providing for 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. The NRC is reviewing three applications for early site permits, and it expects to receive four applications for combined construction and operating licences by the end of 2007, with several more possible in 2008.

24. In Canada, Pickering A-1 became the fourth unit to be reconnected to the grid out of eight that have been shut in recent years. Agreement was also reached on a four-year programme for the fifth and sixth restarts, at Bruce A-1 and Bruce A-2.

A.2. The Future

A.2.1. Rising Expectations[2]

25. 2005 has been a year of rising expectations for nuclear power. In March, high-level representatives of 74 governments, including 25 representatives at the ministerial level, gathered in Paris at a conference organized by the Agency to consider the future role of nuclear power. The vast

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[2] More detail on recent Agency projections is available at http://nesisda2/rds-1/. The Agency's recent and current work on data collection and expert assessment for medium term projections is described in the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/capacity_building.pdf*) and on its website at *http://www.iaea.org/OurWork/ST/NE/Pess/*.

majority of participants affirmed that nuclear power can make a major contribution to meeting energy needs and sustaining the world's development in the 21st century, for a large number of both developed and developing countries. Among them were a number of countries currently without nuclear power programmes, such as Egypt, Indonesia, Morocco, Poland, Turkey and Vietnam. Among the challenges facing countries starting up a nuclear power programme is that of establishing the necessary supporting infrastructure including the legal and regulatory infrastructure.[3]

26. Contributors to the rise in expectations are nuclear power's good and lengthening track record, the persistent growth in global energy needs, new environmental constraints, concerns in some countries about energy supply security, and specific nuclear power expansion plans in countries such as India, China, Japan, the Republic of Korea and the Russian Federation.

27. Nuclear power's good and lengthening track record is reflected in the 11 991 reactor-years of experience shown in Table A-1, improved capacity factors, lower generating costs and an excellent safety record. There has been one accident with major off-site consequences — at Chernobyl in 1986. That accident cost lives and caused widespread misery. But it also brought about major changes including the founding of a 'safety culture' of constant improvement, thorough analysis of experience and sharing of best practices. This safety culture has been demonstrating its effectiveness for nearly two decades, and this safety record provides the basis for countries considering constructing nuclear power plants.

28. Persistently growing global energy needs in the century ahead are projected in all independent analyses and forecasts. If the world is to meet even a fraction of the economic aspirations of the developing world, energy supplies must expand significantly. Oil and natural gas prices rose substantially in 2005, reflecting market expectations that demand will grow faster than supply.

29. Figure A-1 shows the historical growth in worldwide nuclear generating capacity since 1960 plus high and low projections by the Agency as updated in 2005. The difference between the low and the high projections in 2030 is 222 GW(e). As shown in the figure, 66 GW(e) of this difference, or 30%, is accounted for by Western Europe, and 52 GW(e), or 23%, by the Far East.

30. Although expectations for nuclear power are rising, a recent global public opinion survey commissioned by the Agency shows a continuing diversity of views. The survey polled 18 000 people in 18 countries. There was substantial diversity across countries. Aggregated results are shown in Figure A-2. A majority of 62% wished to keep current plants running at the same time that a majority of 59% did not want new plants built. A follow-up question was also asked that included brief information about nuclear power's very low greenhouse gas emissions, following which the percentage in favour of expanding nuclear power rose from 28% to 38%, and the percentage opposing expansion dropped from 59% to 47%.

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[3] Additional documentation is available on IAEA.org under *'Nuclear Technology Review 2006'*.

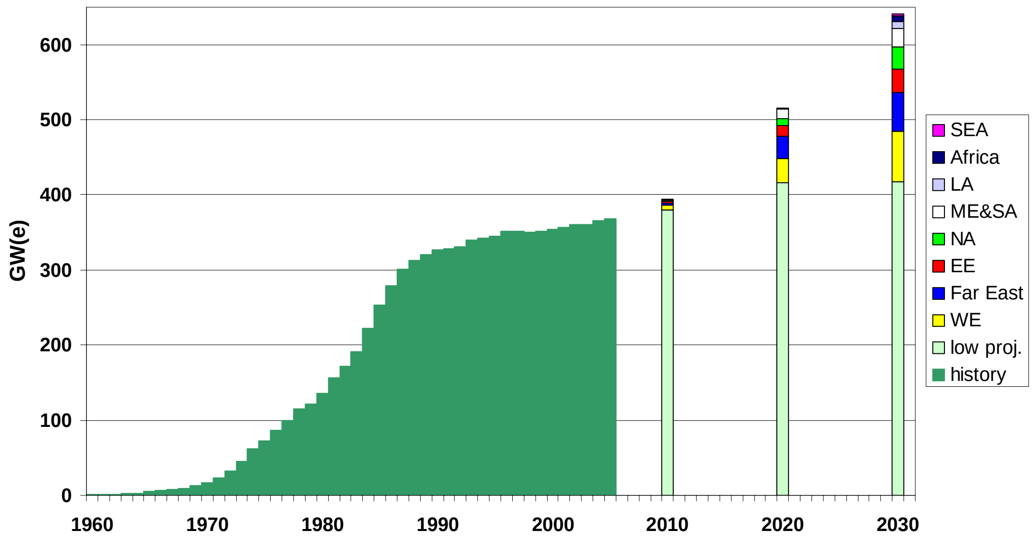

Figure A-1. Installed nuclear power generating capacity worldwide. The dark green bars show historical growth from 1960 through 2005. The light green bars show the Agency's latest low projection for 2010, 2020 and 2030. The other colours show how much of the difference between the Agency's low and high projections is attributable to different regions of the world. (SEA = South-East Asia; LA = Latin America; ME&SA = Middle East and South Asia; NA = North America; EE = Eastern Europe; WE = Western Europe).

Figure A-2. Aggregate results of a global public opinion poll. Source: *Global Public Opinion on Nuclear Issues and the IAEA: Final Report from 18 Countries*, 2005.

A.2.2. Sustainable Development and Climate Change[4]

31. The UN Commission on Sustainable Development (CSD) first took up the topic of energy at its ninth session in 2001, and the relationship between nuclear energy and sustainable development was debated thoroughly. The outcome was twofold. First, parties agreed to disagree, with the final text observing that some countries view nuclear energy as an important contributor to sustainable development and others do not. Second, parties agreed that "the choice of nuclear energy rests with countries." Nuclear power will next be part of the agenda when the CSD again takes up energy issues in 2006 and 2007.

32. The Kyoto Protocol entered into force in February 2005 and 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

[4] More detailed information about Agency 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/Anrep2005/capacity_building.pdf*) and on the Agency's website at *http://www.iaea.org/OurWork/ST/NE/Pess/climate.shtml*.

make nuclear power increasingly attractive. In the past its advantage of very low GHG emissions has been invisible to investors, as the lack of restrictions or taxes on such emissions meant there was no economic value to their avoidance.

33. The 11th Conference of the Parties to the UN Convention on Climate Change (CoP-11) in Montreal in December 2005 was the first to take place after entry into force of the Kyoto Protocol and thus also served as the first Meeting of the Parties to the Kyoto Protocol (MoP-1). As such, it formally adopted the rules for implementing the Kyoto Protocol that were preliminarily adopted at CoP-7 as the Marakkesh Accords. With respect to emission reductions after the first commitment period (2008-2012), it decided to start discussions in an "open-ended ad hoc working group … which… shall aim to complete its work… as early as possible and in time to ensure that there is no gap between the first and second commitment periods". In these discussions, an important issue for nuclear power will be the fate of the current exclusion, during the first commitment period, of nuclear power projects from two of the three flexible mechanisms in the Kyoto Protocol, specifically the clean development mechanism and joint implementation.

A.2.3. Key Issues

Economics

34. 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 NPPs continue to be a generally competitive profitable source of electricity, but for new construction, the economic competitiveness of nuclear power depends on several factors. First it depends on the alternatives available. Some countries are rich in alternative energy resources, others less so. Second, it depends on the overall electricity demand in a country and how fast it is growing. Third, it depends on the market structure and investment environment. Other things being equal, nuclear power's front-loaded cost structure is less attractive to a private investor in a liberalized market that values rapid returns, than to a government that can look longer-term, particularly in a regulated market that assures attractive returns. Private investments in liberalized markets will also depend on the extent to which energy-related external costs and benefits (e.g. pollution, GHG emissions, waste and energy supply security) have been internalized. In contrast, government investors can incorporate such externalities directly into their decisions. Also important are regulatory risks. Political support for nuclear power varies across countries, and, within a given country, it can change over time. An investor must weigh the risk of political shifts that might require cancellation of the project midstream or introduce delays and costs that would vitiate an originally attractive investment. Different countries also have different approval processes. Some are less predictable than others and create greater risks, from the investor's perspective, of expensive interventions or delays.

35. Figure A-3 summarizes new construction cost estimates from seven recent studies.[5] Except for oil-fired electricity generation (estimated in only one study) the high end of each cost range is at least 100% higher than the low end. This is due partly to different technological assumptions across the studies, but also to the factors listed above. Moreover, the ranges in Figure A-3 incorporate only

[5] The Massachusetts Institute of Technology, *The Future of Nuclear Power*, Cambridge, Massachusetts, USA (2003); The University of Chicago, *The Economic Future of Nuclear Power*, Chicago, Illinois, USA (2004); The Royal Academy of Engineering, *The Cost of Generating Electricity*, London, UK (2004); General Directorate for Energy and Raw Materials (DGEMP), French Ministry of the Economy, Finance and Industry, Paris, France (2003); Ministry of Economy, Trade and Industry, Tokyo, Japan (2004); Matt Ayres, Morgan MacRae and Melanie Stogran, *Levelised Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario*, Canadian Energy Research Institute (CERI), Calgary, Alberta, Canada, 2004; Nuclear Energy Agency and International Energy Agency, *Projected Costs of Generating Electricity: 2005 Update*, Organisation for Economic Co-operation and Development, Paris, 2005.

internalized costs. If high enough priority is given to improving national energy self-sufficiency, for example, the preferred choice in a specific situation might not be the least expensive.

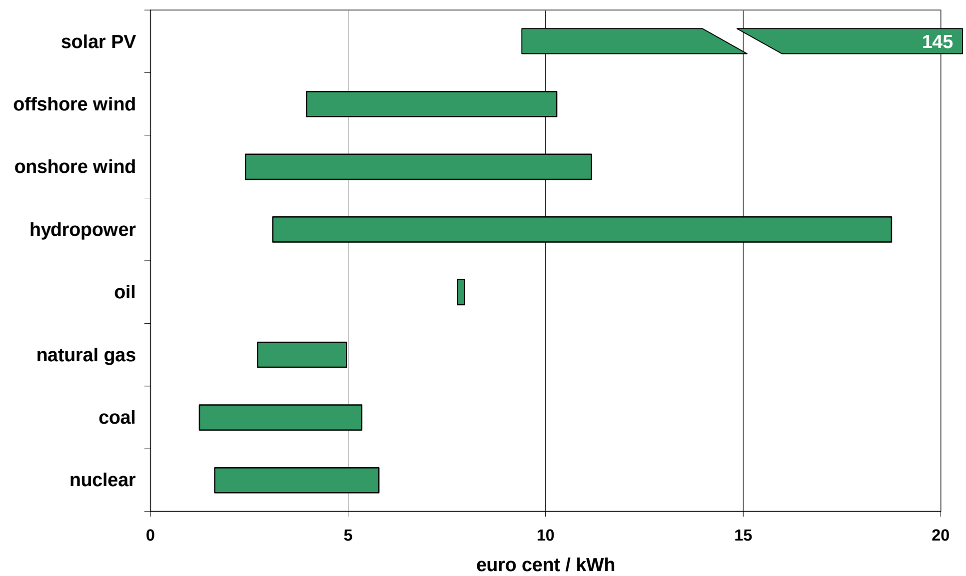

Figure A-3. The ranges of levelized costs associated with new construction as estimated in seven recent studies for electricity generating technologies in different countries. (PV = photovoltaic).

Safety[6]

36. The international exchange of NPP operating experiences and, in particular, the broad dissemination of 'lessons learned' are essential parts of maintaining and strengthening the safe operation of nuclear power plants. Collecting, sharing and analysing operating experience are all vital safety management elements, and there is clear empirical evidence that learning from NPP operating experience has led, and continues to lead, to improvements in plant safety. International mechanisms to facilitate exchange include the World Association of Nuclear Operators (WANO) and the IAEA. Regular meetings of the IAEA/NEA Joint Incident Reporting System are an additional part of this global exchange process, where recent incidents can be discussed and analysed in detail.

37. Safety indicators, such as those published by the World Association of Nuclear Operators and reproduced in Figures A-4 and A-5, improved dramatically in the 1990s. However, in some areas improvement has stalled in recent years, as in the case of unplanned scrams shown in Figure A-4. Also the gap between the best and worst performers is still large, providing substantial room for continuing improvement. Since the 1986 accident at Chernobyl, enormous efforts have been made in upgrading reactor safety features, but facilities still exist at which nuclear safety assistance should be made a priority.

38. More detailed safety information and recent developments related to all nuclear applications are presented in the Agency's annual *Nuclear Safety Review* (GC(50)/INF/2).

[6] More detailed information on Agency activities concerning nuclear safety is available in relevant sections of the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/safety_nuclear.pdf*) and on the Agency's website at *http://www-ns.iaea.org/*.

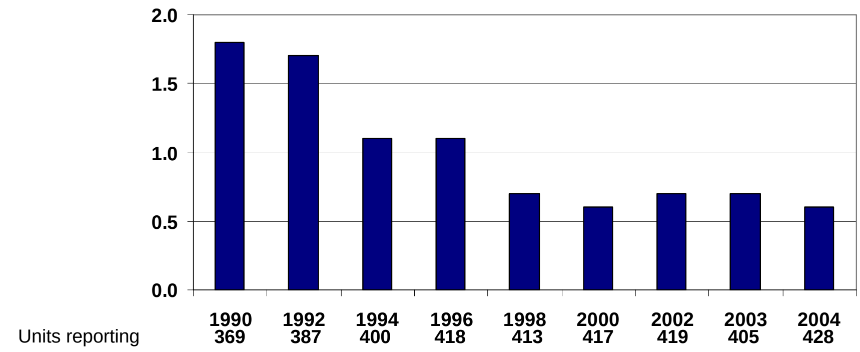

Figure A-4. Unplanned scrams per 7000 hours critical. Source: *WANO 2004 Performance Indicators.*

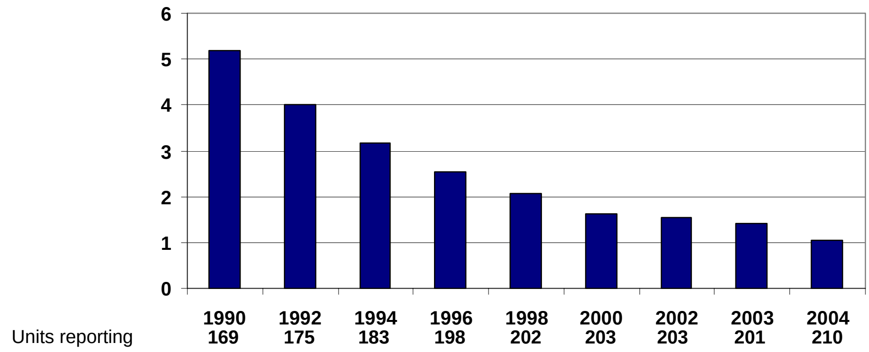

Figure A-5. Industrial accidents at nuclear power plants per 1 000 000 person-hours worked. Source: *WANO 2004 Performance Indicators.*

Spent fuel, reprocessing, waste and decommissioning[7]

39. The world's current 441 operating nuclear power plants generate over 10 000 tonnes of heavy metal (tHM) of spent fuel each year. Less than one third is reprocessed for recycling as mixed-oxide (MOX) fuel. The remainder is placed into interim storage facilities. About 190 000 tHM are currently in storage. Most are stored in water, but an increasing amount is in dry storage, which has become the preferred method for new away-from-reactor interim storage. Dry storage has the advantage of being modular, which spreads capital investments over time, and, in the longer term, the simpler passive cooling systems used in dry storage reduce operation and maintenance requirements and costs.

40. Current global capacity for reprocessing civilian spent fuel is approximately 5000 tonnes of heavy metal per year (tHM/a). A new facility under construction at Rokkashomura, Japan will add 800 tHM/a. Uranium commissioning at Rokkashomura began in 2004, active commissioning with actual spent fuel is scheduled to begin in 2006, and commercial operation is scheduled for 2007. Current global capacity for MOX fuel fabrication is approximately 200 tHM/a and is expected to grow to around 350 tHM/a by 2010.

[7] Additional documentation is available on IAEA.org under *'Nuclear Technology Review 2006'*. More detailed information on the Agency's activities on decommissioning, spent fuel and waste is available in relevant sections of the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/nuclear_fuel_cycle.pdf* and *http://www.iaea.org/Publications/Reports/Anrep2005/radioactive_waste.pdf*) and on the Agency's website at *http://www.iaea.org/OurWork/ST/NE/NEFW/index.html* and http://www-ns.iaea.org/home/rtws.asp.

41. Current research to improve on the PUREX process used in all operating commercial reprocessing plants (and Rokkashomura) covers advanced PUREX processes, other aqueous processes and several non-aqueous processes.

42. The most efficient way to use reprocessed fuel is in fast reactors. Fast reactors have been built and operated in France, Germany, India, Japan, the Russian Federation, the UK and the USA. However, early economic incentives for reprocessing and recycling diminished after the 1970s, partly because of the slowdown in nuclear capacity growth, partly because uranium resource estimates continually rose and partly because of secondary sources. Only one fast reactor, BN-600 in the Russian Federation, currently operates as a power reactor, and it uses not reprocessed fuel, but fresh highly enriched uranium (HEU) fuel. India, however, began construction in 2004 of a 500 MW(e) prototype fast breeder reactor at Kalpakkam, and there is ongoing research in a number of countries (see Section B.1).

43. Finland, Sweden and the USA are furthest along in developing final high level waste repositories, although none is expected to be in operation much before 2020. Finland and the USA have each chosen a single site, at which they are conducting the necessary research. A licence application for the repository at Yucca Mountain, USA, was scheduled for submittal to NRC in 2004, but has been delayed. Sweden is conducting research at two possible sites.

44. In November 2005, following a three-year nation-wide consultative process, Canada’s Nuclear Waste Management Organization (NWMO) recommended an ‘adaptive phased’ approach to managing Canadian spent fuel. During the next 30 years spent fuel would continue to be stored at reactor sites, a suitable site for a deep geological repository would be selected, and a decision would be made whether to also construct a centralized interim shallow underground storage facility to start receiving spent fuel in about 30 years. With or without a centralized interim facility, the deep repository would begin accepting spent fuel in about 60 years.

45. In France, investigations at the underground research laboratory in Bure on disposal in clay have made good progress. France’s 1991 nuclear waste research and development act specifically requires further parliamentary action after 15 years, and a formal public debate began in 2005 as preparation for such action in 2006. The debate is based on research since 1991 on three main approaches — partitioning and transmutation, geological disposal, and conditioning and long term interim storage — and the new legislation is expected to clarify near-term and intermediate-term steps to be taken to move forward on all three.

46. Regarding disposal of low and intermediate level radioactive waste, noteworthy developments took place in 2005 in Belgium, Hungary and the Republic of Korea. In Belgium, at least two communities voted to become candidate sites for a national low level waste (LLW) repository. In Hungary, residents of Bataapati voted overwhelmingly to host the country’s final repository for LLW and intermediate level waste (ILW). And in the Republic of Korea, Gyeongju was designated as the site for the first LLW and ILW repository, conditional on a successful geological site assessment, after almost 90% of Gyeongju’s voters approved, compared with 67 to 84% in three other candidate communities.

47. In 2005, decommissioning of the Trojan and Maine Yankee NPPs in the USA was completed. Except for their separate spent fuel storage facilities, both sites were released for unrestricted public use. Thus, by the end of 2005, eight power plants around the world have been completely decommissioned with their sites released for unconditional use. Seventeen plants have been partially dismantled and safely enclosed, 31 are being dismantled prior to eventual site release, and 30 are undergoing minimum dismantling prior to long-term enclosure.

Proliferation Resistance[8]

48. Non-proliferation concerns have increased in the past few years. Proliferation resistance is a characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology. As part of the Generation IV International Forum (GIF) and the Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) increased attention is being paid to the issue of intrinsic proliferation resistance features, i.e. those features that result from the technical design of nuclear energy systems. These are summarized in Section B.1 on advanced fission.

49. In January 2006, 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 Agency. In February 2006, the USA announced a Global Nuclear Energy Partnership to develop advanced recycling technologies that would not separate plutonium; international collaboration in supplying fuel for States who agree not to pursue enrichment and reprocessing; advanced reactors to consume recycled spent fuel while providing energy; and safe and secure small reactors well suited to the needs of developing countries.

A.2.4. Resources[9]

50. *Identified conventional uranium resources* are currently estimated at 3.8 million tonnes (MtU) for resources recoverable at costs below $80/kg and at 4.7 MtU for costs below $130/kg. For reference, the spot market price of uranium at the end of May 2006 was $112/kg. For both categories these estimates have increased in the last two years due both to new discoveries and to the reallocation of some resources from higher cost categories to lower cost categories.

51. *Undiscovered conventional resources* add another estimated 7.1 MtU at costs less than $130/kg. This includes both resources that are expected to occur either in or near known deposits, and more speculative resources that are thought to exist in geologically favourable, yet unexplored areas. There are also an estimated further 3.0 MtU of speculative resources for which production costs have not been specified.

52. *Unconventional uranium resources and thorium* further expand the resource base. Unconventional uranium resources include about 22 MtU that occur in phosphate deposits and up to 4000 MtU contained in seawater. The technology to recover uranium from phosphates is mature with estimated costs of $60–100/kgU. The technology to extract uranium from seawater has only been demonstrated at the laboratory scale, and extraction costs are currently estimated at $300/kgU. Thorium is three times as abundant in the earth's crust as uranium. Although existing estimates of thorium reserves plus additional resources total more than 4.5 Mt, such estimates are considered still conservative. They do not cover all regions of the world, and the historically weak market demand has limited thorium exploration.

53. Figure A-6 compares the geographical distribution of identified conventional uranium resources with the distribution of uranium production in 2004. Three countries — Australia, Canada and Kazakhstan — account for 50% of the identified conventional resources and for 60% of production.

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[8] More detailed information on Agency activities concerning proliferation resistance and safeguards is available in relevant sections of the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/safeguards.pdf*) and on the Agency's website at *http://www.iaea.org/OurWork/SV/Safeguards/index.html*.

[9] More detailed information on Agency activities concerning nuclear resources is available in relevant sections of the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/nuclear_fuel_cycle.pdf*), on the Agency's website at *http://www.iaea.org/OurWork/ST/NE/NEFW/nfcms_home.html* and on IAEA.org under "Nuclear Technology Review 2006.

54. Uranium production in 2004 totalled 40 263 tU, only about 60% of the world's reactor requirements (67 320 tU). The remainder was covered by five secondary sources: stockpiles of natural uranium, stockpiles of enriched uranium, reprocessed uranium from spent fuel, MOX fuel with ^{235}U partially replaced by ^{239}Pu from reprocessed spent fuel and re-enrichment of depleted uranium tails (depleted uranium contains less than 0.7% ^{235}U).

55. Of these five secondary sources, the largest contributions come from stockpiles built up from the beginning of commercial exploitation of nuclear power in the late-1950s through to about 1990. Throughout this period uranium production consistently exceeded commercial requirements due mainly to slower than expected growth in nuclear electricity generation plus high production for military purposes. Since 1990 the situation has been reversed, and stockpiles have been drawn down. However, precise information is not readily available, and possible future political decisions on releasing military material for commercial purposes add an additional element of uncertainty.

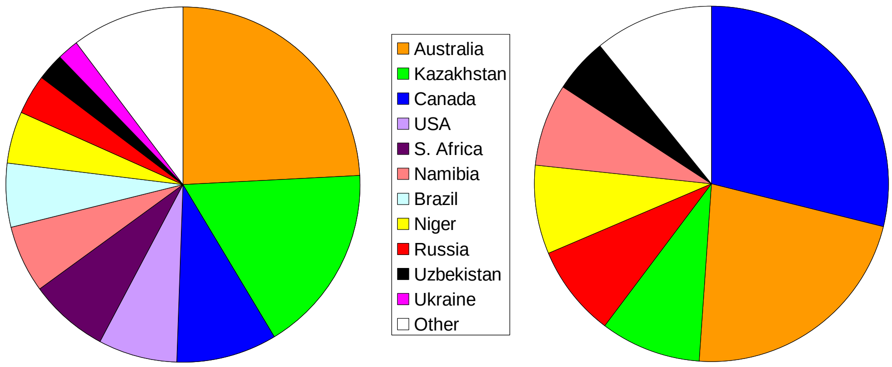

Figure A-6. Geographical distribution of identified conventional uranium resources (left) and of uranium production in 2004 (right).

56. Recycling of spent fuel as MOX fuel has not significantly altered uranium requirements, given the relatively small number of reactors using MOX and the limited number of recycles possible using current reprocessing and reactor technology. Uranium recovered through reprocessing of spent fuel, known as reprocessed uranium, is currently recycled only in France and the Russian Federation. Available data indicate that it represents less than 1% of world requirements.

57. Depleted uranium stocks are substantial, estimated at about 1.5 MtU at the beginning of 2005. Re-enrichment, however, is currently only economical in centrifuge enrichment plants that have spare capacity and low operating costs. Complete data are unavailable, but European Union (EU) statistics show that deliveries of re-enriched tails from the Russian Federation were 6% of the total uranium delivered to EU reactors in 2004.

58. Uranium prices generally declined from the early-1980s until 1994 due to over-production and the availability of secondary sources, and between 1990 and 1994 low prices led to significant reductions in many sectors of the world uranium industry. Beginning in 2001, however, the price of uranium has rebounded to levels not seen since the 1980s, with the spot price increasing more than six-fold from 2001 to 2006.

59. Table A-2 summarizes the potential longevity of the world's conventional uranium resources. For both the current LWR once-through fuel cycle and a pure fast reactor fuel cycle, the table estimates how long conventional uranium resources would last, assuming electricity generation from nuclear power stays at its 2004 level.

Table A-2. Years of Resource Availability for Various Nuclear Technologies

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
Current fuel cycle (LWR, once-through)	85	270
Pure fast reactor fuel cycle with recycling	5000–6000	16 000–19 000

B. ADVANCED FISSION AND FUSION[10]

B.1. Advanced Fission

60. In the near term most new nuclear plants will likely be evolutionary improvements on existing designs. In the longer term, more innovative designs that incorporate radical changes and promise significantly shorter construction times and lower capital costs could help to promote a new era of nuclear power. Several innovative designs are in the small (< 300 MW(e)) to medium (300–700 MW(e)) size range. Such designs could be attractive for the introduction of nuclear power in developing countries and for remote locations.

61. Advanced designs seek improvements in three principal areas: cost reductions, safety enhancements, and proliferation resistance.

62. For cost reductions, some designs emphasize further developing proven strategies, i.e. economies of scale through larger units; shorter construction schedules through modular systems and addressing licensing issues early; standardization and construction in series; multiple unit construction; and enhancing local participation, while other designs emphasize new cost reduction strategies including economies of series production; sharpening the accuracy of codes and databases to eliminate over-design; developing ‘smart’ components to detect incipient failures and reduce dependence on costly redundancy and diversity; passive safety systems; further development of probabilistic safety analysis to support plant simplification and risk-informed regulatory decision making; fewer components requiring nuclear grade standards; and higher thermal efficiencies.

63. With respect to safety, work on technical improvements includes larger water inventories (in the case of water cooled reactors), lower power densities, larger negative reactivity coefficients, redundant and diverse safety systems with proven high reliability, and passive cooling and condensing systems.

64. With respect to proliferation resistance, intrinsic measures incorporated into various advanced designs concern the chemical form of nuclear material; its mass and bulk, radiation field, heat generation and spontaneous neutron generation rate; the complexity of modifications necessary to use a civilian facility and material for weapons production; and design features that limit access to nuclear material.

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[10] More detailed information on Agency activities on advanced fission is available in relevant sections of the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/nuclear_power.pdf*) and on the Agency’s website at *http://www.iaea.org/OurWork/ST/NE/NENP/NPTDS.html*. Information on the Agency’s activities on fusion is also available in the latest Annual Report (*http://www.iaea.org/Publications/Reports/Anrep2005/nuclear_science.pdf*). A status report prepared by the International Fusion Research Council and summarizing progress in fusion research over the past decade was published in the journal *Nuclear Fusion* in 2005 (*Nuclear Fusion* 45 (2005) A1–A28).

65. Important design efforts on large advanced light water reactors (LWRs) are underway in Argentina, China, the European Union, France, Germany, Japan, Republic of Korea, Russian Federation and USA. Both Canada and India are working on advanced heavy water reactor designs, and advanced gas cooled reactor designs are being developed in China, France, Japan, Republic of Korea, Russian Federation, South Africa and USA. The design and safety review of a demonstration unit of the 168 MW(e) pebble bed modular high-temperature reactor in South Africa has been completed and a licensing review is underway. For liquid metal cooled fast reactors, development activities are underway in China, France, India, Japan, Republic of Korea and Russian Federation.

66. Complementing the initiatives above are two major international efforts to promote innovation — the Generation IV International Forum (GIF) and the Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). GIF has reviewed a wide range of innovative concepts and, in 2002, selected six types of reactor systems for future bilateral and multilateral cooperation: 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. A *Framework Agreement on International Collaboration in Research and Development on Generation IV Nuclear Energy Systems* was signed by Canada, France, Japan, UK and USA in February 2005. The agreement clarifies explicit ground rules for joint research and other cooperative activities and provides the foundation on which specific GIF projects can now be negotiated.

67. In 2004, INPRO published revised guidelines and a methodology for evaluating innovative nuclear energy systems (INSs). Current activities include completion of a user manual on the INPRO methodology to assist users in assessing INSs; application of the methodology to assessing INSs in national and multinational studies; analyses of the role and structure of INSs to meet national, regional and global energy demands in a sustainable manner; and selection of the most suitable areas for collaborative development. In 2005 INPRO grew to 24 members, with the addition of Ukraine and the United States of America.

B.2. Fusion

68. In June 2005 a joint declaration of all parties to the International Thermonuclear Experimental Reactor (ITER) negotiations was signed, and agreement reached on the construction site at Cadarache, France. This decision signalled an important new stage in the development of fusion energy — the scientific and engineering demonstration of fusion technology in conditions relevant to operating a fusion reactor for power production. In December 2005 India became the seventh member of ITER.

69. Harnessing nuclear fusion energy presents many challenges, including the increased need for access to reliable, comprehensive atomic and molecular data. With the approaching construction of ITER, many atomic, molecular and plasma-surface interaction issues have taken on increased importance. Several significant issues have been identified by the International Fusion Research Council[11] (IFRC), such as tritium inventory and removal, edge plasma physics, and heavy element impurities. An initiative will be launched in 2006 to study and quantify the erosion properties of fusion reactor containment wall materials that will have a direct influence on the understanding of tritium absorption by wall components.

70. An improved understanding of the physics of confined plasmas is leading to improved parameters for optimized operation of fusion power plants. Alternative magnetic confinement schemes such as spherical tokamaks and stellarators (devices used to confine hot plasma with magnetic fields to

[11] The IFRC published a "Status Report on Fusion Research" in the journal *Nuclear Fusion* in 2005 (*Nuclear Fusion* 45 (2005) A1–A28), summarizing the progress in fusion research during the last decade.

sustain a controlled nuclear fusion reaction) have also made significant progress in terms of achieved operational parameters. Wendelstein-7X, the world's largest stellarator under construction in Germany and planned to go into operation by 2010, will boost research on the topic of steady state operation for fusion power plants.

71. Progress in understanding the physics in inertial fusion research has led to the design and fabrication of two megajoule laser facilities for fusion ignition experiments; the National Ignition Facility of the USA is being built at Livermore, and the Laser Megajoule facility near Bordeaux in France. They are expected to be ready for experiments in 2008–2010. A new approach to inertial fusion, called the fast ignition approach, is also under development, requiring the use of an ultra-intense laser. The development of sub-pico-second ultra-intense lasers is already at an advanced stage in the Fast Ignition Realization Experiment (FIREX) programme in Osaka, Japan.

C. ATOMIC AND NUCLEAR DATA

72. A wide and comprehensive range of atomic and nuclear data is an essential pre-requisite for basic nuclear physics research and the successful planning, design and operation of nuclear power plants and associated reprocessing and waste handling facilities, as well as for applications such as nuclear medicine and specific nuclear-based analytical techniques. Increasing interest in the use of accelerator driven systems (ADS) will lead to a higher demand for reliable nuclear data of high quality for both reactor physics/engineering purposes and radiation transport computations.

73. More reliable data have been generated to ensure improved confidence in fission and fusion assessments, including such important parameters as the thermal neutron cross section of uranium-238, thermal scattering law data, updated cross sections for neutronics calculations of fusion devices and ADS, and other important atomic and nuclear parameters. Other advances in the compilation and evaluation of atomic and nuclear data continue, for example, to produce atomic and molecular data for plasma modelling and for heavy element impurities in fusion reactors.

D. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

D.1. Accelerators

74. The utilization of charged particle accelerators, in particular proton accelerators and electron accelerators, continues to provide significant developments in the fields of advanced materials, health care, and physical and life sciences. Notable trends are the emergence of new applications such as the use of focused ion beams, e.g. for micromachining, in nanotechnology and in cell irradiation techniques.

75. Interest is developing in non-standard material behaviour in the field of ion beam applications. For example, research is leading to improved knowledge concerning the relationship between structure and properties of the next generation of insulating materials.

76. Two new pulsed spallation sources (one of the processes by which a particle accelerator may be used to produce a beam of neutrons) are under construction in Japan and the USA. Existing spallation sources, e.g. ISIS in the UK and SINQ in Switzerland, are being upgraded and new applications in physics, semiconductor physics, magnetism, and biology are emerging.

D.2. Research Reactors

77. Radioisotope production, neutron beam applications, silicon doping and material irradiation continue to be the main applications in many research reactor facilities. New research reactors are under construction, such as the OPAL Reactor in Australia, the China Advanced Research Reactor (CARR) in China and TRIGA-II in Morocco, or have been commissioned recently, such as FRM-II in Germany and the Miniature Neutron Source Reactor (MNSR) in Nigeria. In Belgium, development of a new accelerator driven irradiation facility, MYRRHA, is at an advanced stage. MYRRHA is intended to serve as a European multipurpose research facility.

78. The FRM-II in Germany is designed for neutron beam utilization and has features that include a secondary neutron source, and accessories such as neutron guides for special experiments. These features are useful in studies of soft matter-polymers, biological species and liquids and disordered materials. The MNSR research reactor in Nigeria, on the other hand, will extensively be used for activation analysis for applications in areas such as environment, food and agriculture.

79. Multipurpose research reactors, such as the OPAL reactor in Australia and CARR in China, are expected to become operational in 2006 with radioisotope production, silicon doping and neutron beam applications[12] as major activities.

80. The Reduced Enrichment for Research and Test Reactors (RERTR) Programme seeks to convert research reactors using highly enriched uranium (HEU) fuel to low enriched uranium (LEU) fuel. Continuing support for the development and qualification of high density LEU fuels and for fostering fission molybdenum-99 production using LEU targets are other activities under the RERTR Programme.

81. There are concerns about the future reliability of radioisotope availability, if due attention is not paid now to meet future research reactor irradiation needs. There are only four major industrial producers of molybdenum-99, but many more research reactors are used for irradiating HEU/LEU targets. There is no discernible trend for the industrial companies considering a switch to use of LEU targets, and RERTR Programme participants have focussed additional attention on this issue. The successful demonstration by the National Atomic Energy Commission (CNEA), in Argentina, of medium scale regular production of molybdenum-99 using locally produced LEU targets, is a notable advance in this regard.

[12] Additional documentation is available on IAEA.org under *'Nuclear Technology Review 2006'*.

E. RADIOISOTOPE APPLICATIONS AND RADIATION TECHNOLOGY

E.1. Radioisotope Applications

82. More than 150 different radioisotopes in various forms are in use for diverse applications in many sectors of economic significance, including medicine, food processing, industry, agriculture, structural safety and research. The potential for expanding radioisotope applications and spreading the benefits to developing countries continues to be high. Radioisotopes are produced in at least twenty-five countries, while more than thirty additional countries are likely producers of isotopes as reported in an IAEA/OECD survey[13]. The medical field accounts for the majority of isotope applications, followed by industry and research.

83. Radionuclide generator systems continue to play a key role in providing both diagnostic and therapeutic radioisotopes for various applications in nuclear medicine, oncology and interventional cardiology. The use of yttrium-90 for radionuclide therapy is favoured because the parent radionuclide, strontium-90, is available in large quantities from spent-fuel reprocessing. The recovery of strontium-90 followed by large-scale centralized separation of yttrium-90 or production of radionuclide generators could become a major radiochemical process in countries possessing fuel reprocessing facilities.

84. Interest in establishing medical cyclotrons for radioisotope production is growing in many developing countries. Production of radioisotopes of iodine by using an enriched tellurium target is being explored as an economical mode of production.

E.2. Radiation Technology

E.2.1. Nanotechnology for Industry and Health

85. Radiation curable polymeric nano-composites with enhanced surface-mechanical properties have been developed in Germany. Transparent, scratch and abrasion resistant coatings have been produced by radiation curing of acrylate formulations containing high amount of nano-sized modified silica and alumina fillers.

86. Macroscopic polymer gels are now well-established biomaterials typically used as soft contact lenses, hydrogel wound dressings and devices for controlled drug delivery. There is a growing interest in synthesis, properties and applications of microscopic polymer gels, i.e. microgels and nanogels. Nanogels are submicron size cross-linked polymer structures of sizes similar to a single polymer molecule in solution. Such gels have potential applications as drug and gene carriers, polymeric drugs, biomarkers, also as substrates for separation and adsorption of bio-molecules. Nanogels are mostly obtained by emulsion polymerization. Intra-molecular cross-linking of single polymer coils by short pulse electron irradiation of dilute solutions has been proposed by a group in Poland and has the advantages of absence of monomers, cross-linking agents and other potentially toxic compounds, which are needed in conventional processes.

87. Electron beam lithography for direct writing technology has been in extensive use for the fabrication of nano-scale integrated circuit devices. An electron beam lithographic tool was used by university researchers in Glasgow, UK, to fabricate features as small as 20 nm diameter on 100 nm pitch which provide arrays of nano-dots for use in cellular engineering.

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[13] Beneficial Uses and Production of Isotopes, Nuclear Energy Agency, OECD and IAEA Publication, No. 5293, 2005.

E.2.2. Industrial Process Monitoring

88. Radiotracer and sealed source techniques continue to be widely used in various industries to achieve better control of production processes, to improve process efficiency, to enhance product quality and quantity and to verify the information obtained by other methods.

89. Industrial process tomography can provide detailed information on the density distribution of designated cross sections of a chemical reactor. Gamma transmission tomography is currently used by developers and manufacturers of chemical process systems to measure the spatial density distribution inside processing vessels or pipelines. However, development of a standard industrial tomographic scanner for in-situ applications is complex, because of the variety of locations, environments and differing designs of industrial process columns. The development of portable/transportable tomographic imaging systems using radioisotope sources will in future be significant as an indispensable diagnostic tool for industrial processes and systems.

90. The single photon emission computed tomography (SPECT) technique, which is largely used in nuclear medicine, is soon likely to be used for diagnosis of industrial reactors. The information obtained from SPECT will be more reliable and specific than that from other methods. Gamma emission tomography is an emerging method in investigating flow dynamics in industrial reactors. For example, liquid flow distribution in trickle bed reactors was investigated using this technique. Figure E-1 shows an example of an investigation of the radial distribution of liquid flow in an industrial column, such as is found in a refinery.

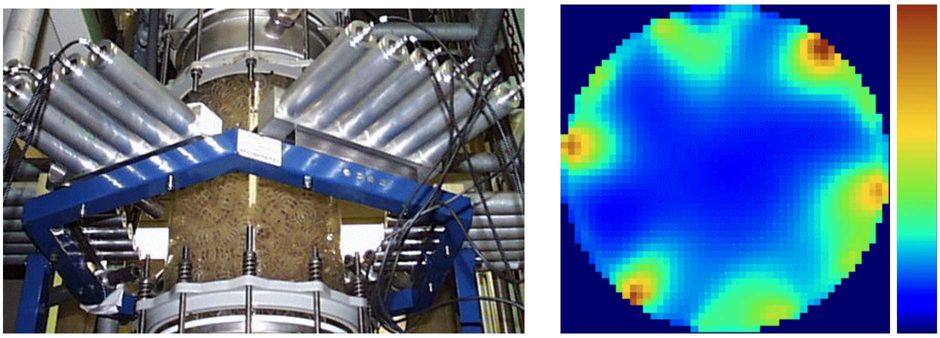

Figure E-1. A tomography system with 36 collimated detectors is installed around the column. The liquid phase, labeled with 1.9 GBq of technetium-99m, is injected, and the result shows some water channeling on the wall of the column.

F. NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

F.1. Crop Improvement and Protection

91. Nuclear techniques provide useful tools for plant breeders and play a significant role in crop improvement. Applications of nuclear techniques in this area include mutation induction for increasing germplasm variability using gamma rays, X-rays and fast neutrons; labelling of nucleic acids used as probes for genetic fingerprinting, mapping and marker assisted selection; and mutagenesis for the analyses of gene function.

92. Induced mutations created by gamma rays, X-rays, fast neutrons or chemicals have led to major successes in plant breeding. Beneficial mutants have been selected and used by plant breeders for over 50 years. To date, nearly 2 500 officially registered mutant varieties of more than 160 plant species worldwide are listed in the FAO/IAEA Mutant Variety Database. For example, a mutant rice cultivar (VND95-20) with high quality and tolerance to salinity has been released in Vietnam and is one of the five top export rice varieties, occupying 28% of the one million hectare export rice area in the Mekong Delta. The salt tolerant rice cultivar target area for Bangladesh, India, Philippines and Vietnam alone is estimated at 4.3 million hectares.

93. Deciphering gene function is now a major objective in genetics. The large amounts of readily available DNA sequence information and induced mutants are becoming key elements in genetic studies as they provide the resources for the systematic discovery and functional analysis of genes. Targeting induced local lesions in genomes (TILLING) is one example of a technique where mutants for targeted genes can be rapidly identified. This technique is now being applied to rice, wheat and barley and shows significant potential as a method for dissecting the genes that control or influence the valuable traits in diverse crops.

94. The use and transboundary shipment of sterile insects has so far been excluded from the International Standards for Phytosanitary Measures No. 3 (ISPM 3), *"Code of Conduct for the Import and Release of Exotic Biological Control Agents*", of the International Plant Protection Convention (IPPC) because biological control agents were defined as self-replicating organisms. In April 2005, a revised ISPM 3 entitled "*Guidelines for the Export, Shipment, Import, and Release of Biological Control Agents and Other Beneficial Organisms*" was approved that explicitly includes sterile insects as beneficial. In addition, the terms "sterile insect" and "sterile insect technique" (SIT)[14] were included in the IPPC *Glossary of Phytosanitary Terms*. This will facilitate the application of SIT in Member States and shows that the use of sterile insects as part of the integrated management of plant pests is now internationally recognized under the World Trade Organization's Agreement on the Application of Sanitary and Phytosanitary Measures.

F.2. Animal Production and Health

95. Molecular and nuclear related diagnostics are of particular interest in animal health because they can increase the sensitivity and specificity of methods to detect animal diseases to a previously unachievable level. Notwithstanding the increasing use of non-radioactive methods, a need remains to use radioisotopes for the identification and characterization of proteins, DNA and ribonucleic acid (RNA) because of the achievable high levels of sensitivity. Developments in micro-fabrication, micro-fluidics and nanotechnology offer possibilities for the production of more sensitive, rapid and robust devices that perform under diverse conditions. So-called 'lab-on-a-chip' devices offer the ability to integrate complex laboratory diagnoses (sample processing, target amplification and detection, and detection differentiation) in a single miniaturized device. An important goal in the current development of diagnostic devices is to make them usable in the field, thereby shortening reaction time for implementation of preventative or control measures. In addition to the more classical nuclear technologies, nuclear-based gene expression methods are providing a deeper understanding of nutritional, reproductive and disease elements that lead to simple-to-use manipulations for enhancing livestock productivity.

96. Historically, radioimmunoassay (RIA), which employs radioisotopes in the measurement of the concentration of a given molecule in a biological sample, has been the dominant technology in the field of animal reproduction and breeding. Radioisotopes also serve as the basis for a number of

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[14] Additional documentation is available on IAEA.org under *'Nuclear Technology Review 2006'*.

technologies that deal with the labelling of nucleotides. By incorporating radioisotopes (such as phosphorus-32, phosphorus-33, or sulphur-35) into short DNA synthetic probes, researchers have a way to identify DNA polymorphism (which permits the identification of genes influencing traits of interest) and confirm parentage and/or measure the quantity of DNA or RNA in a given biological sample. Subsequent testing can determine which animals carry the superior forms of genes of interest and this information can be used to improve accuracy of selection and, in turn, increase productivity. In addition, identification and tracing of DNA polymorphisms can contribute to the genetic characterization of desired breeds and emphasize genetic conservation. Novel technologies such as dual energy X-ray absorptiometry, magnetic resonance spectroscopy and computer tomography may provide methods to determine body composition, carcass quality and muscularity without the need to slaughter animals.

97. Recent developments in improving the specificity of radioimmunoassays for leptin (a protein hormone that plays a key role in metabolism and regulation of adipose tissue) and insulin-like growth factors and extended knowledge of their mechanisms of action indicate possibilities for their use (alone or in combination with oxygen-18 and hydrogen-2 labelled water) and also for the use of carbon-13 or carbon-14 carbon dioxide entry rate techniques to assess the nutritional, reproductive and energy status of animals. Non-invasive nuclear techniques such as proton induced X-ray emission, proton induced gamma ray emission, thermal ionization mass spectrometry, induced coupled plasma mass spectrometry and X-ray fluorescence spectroscopy for elemental analysis increasingly find nutritional and toxicological applications in livestock studies.

F.3. Food Quality and Safety

98. Food control systems need to take account of the entire food production chain to ensure the quality, safety and wholesomeness of plant and animal products intended for human consumption, aspects also of importance to transboundary trade. More governments are now implementing this concept, in part as a result of increasing consumer concerns about food safety. Nuclear and related techniques assist governments in implementing a food chain approach by developing methodologies, indicators and guidelines that protect food chains from safety hazards at their source through good agricultural practices, including a coordinated approach in the application of best water management practices. These activities include the improvement of laboratory quality management and analytical techniques to meet international standards for pesticides, mycotoxins and veterinary drug residues. They include the adoption of the collaboratively developed Codex Guidelines on the Use of Mass Spectrometry (MS) for Identification, Confirmation and Quantitative Determination of Residues, from the 28th session of the FAO/WHO Codex Alimentarius Commission.

99. The success of the application of previously adopted international standards related to the use of ionizing radiation, now used by over 50 countries worldwide, for the control of food-borne pathogens and insect pests is reflected in part by the recent enactment of harmonized regulations in five more countries for various types of food.

100. Other activities related to the application of international standards for consumer protection and the facilitation of agricultural trade include an online database[15] of government first actions in response to a nuclear emergency affecting agriculture. International trade from affected regions will also be enhanced through collaborative efforts in the revision and expansion to cover additional isotopes of the Codex Guideline Levels for Radionuclides in Foods Following Accidental Nuclear Contamination for Use in International Trade, and for a period greater than one year following a nuclear accident or radiological event.

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[15] The database may be accessed at http://www.iaea.org/programmes/nafa/dx/emergency/index.html.

G. HUMAN HEALTH

G.1. Nutritional and Health-related Environmental Studies

101. Stable isotope techniques have in the past been used as nutritional research tools but are now also used for developing and evaluating nutrition programmes. The techniques can be applied in the most vulnerable population groups, i.e. infants and children, because only stable (non radioactive) isotopes are used. The sensitivity and specificity of measurements, as compared to conventional techniques, are increased by use of stable isotopes. For example, a better understanding can be achieved of the efficacy of nutrition interventions based on changes in body composition (muscle mass) measured by stable isotope techniques. Such techniques can address the need to evaluate locally appropriate, sustainable food based strategies on nutritional status in people living with HIV/AIDS and emphasize the importance of integrating nutrition into a comprehensive response to HIV/AIDS, as recently highlighted by the World Health Organization.

G.2. Nuclear Medicine in Imaging[16] and Therapy

102. Positron emission tomography (PET) imaging is now a dominant topic of most medical imaging meetings, and there has been a remarkable increase in PET publications (see Figure G-1). This technique, using ultra short lived radioisotopes attached to biological markers, allows nuclear medicine physicians to track organ function at the molecular level. In particular, with the use of radio-labelled glucose referred to as FDG (fluoro-18 deoxyglucose) or C11-choline, organs can be explored with respect to glucose and amino acid metabolism. PET images fused with X-ray computed tomography (CT) images provide intricate detail and true quantitative health changes in individual patients, thus leading to changes in the way in which disease is managed.

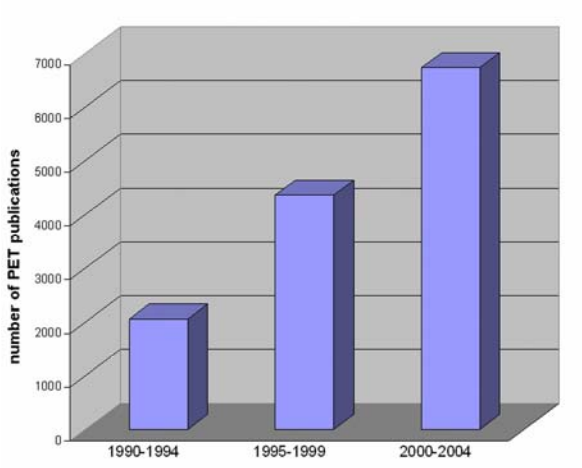

Figure G-1. The development of scientific publications on PET in biomedical scientific journals (source: Medline) over the last 15 years, reflecting the impact that the technique has on imaging of cancer and other diseases.

103. Within the past few decades, advances in computer speed have fostered a revolution in medical imaging technology. Within the next decade it is expected that most modern radiology departments will acquire flat panel imagers, thereby becoming ‘filmless’ and completing the transition to digital technology. The abandonment of chemical processing of film is cost-effective, leading to substantial improvements in image quality and reliability, and has the potential to lead to an overall reduction in exposure to patients from diagnostic X-rays. These advances, coupled to the inherently digital nature of computed tomography systems provides the basis for an electronic medical recording system that

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[16] Additional documentation is available on IAEA.org under *‘Nuclear Technology Review 2006’*.

could contain the entire medical file of individual patients, including all their life-long imaging studies.

104. A major development in the application of nuclear medicine therapeutics is the routine use of radiolabelled anti-CD20 monoclonal antibodies for lymphoma and radiolabelled peptides especially for neuro-endocrine tumours. This finally brings in a new era in targeted therapeutics, which has significantly fewer side effects compared with conventional chemotherapy. A wide variety of radiopharmaceuticals is also available to the nuclear medicine community for providing effective palliation. These are especially useful for metastatic conditions where radiotherapy is not possible, thus providing cost effective improvement in quality of life. Radiolabelled therapeutic antibodies are leading to significant improvements in patient care and, when combined with chemotherapeutic agents, an increase in the overall survival rates.

G.3. Dosimetry and Medical Radiation Physics

105. The leading edge in cancer treatment technology now is called ‘dose painting’ and it is driven by advances in functional imaging. With the advent of magnetic resonance imaging (MRI), it became possible to perform spectroscopic studies or acquire functional MRI images that revealed areas of the tumour with different levels of activity. However, over the past few years PET has become the principal driver of functional imaging. It is now possible to locate areas within tumours that may require higher levels of radiation dose, for example, because the cells appear to be deficient in oxygen, and therefore resistant to radiation, or because the local blood supply is undergoing rapid expansion, perhaps revealing an aggressive disease site. This ability will almost certainly lead to a dose, modified and delivered to different functional parts of the tumour. Dose painting may be altered from one therapy session to the next by using functional imaging studies to periodically monitor the tumour response.

G.4. Radiopharmaceuticals

106. Technetium-99m remains the most widely used radioisotope in diagnostic nuclear medicine worldwide, with over 40 000 procedures performed every day. Use of radiopharmaceuticals in diagnostic nuclear medicine is continuing to grow at a rate of 10-15% annually.

107. The use of therapeutic radiopharmaceuticals is increasing and many new radiopharmaceuticals using particle-emitting radionuclides are under development. Several yttrium-90 based radiopharmaceuticals for cancer therapy and treatment of arthritis are now in the clinical trial stage and their widespread future application is envisaged. Lutetium-177, an ideal therapeutic radionuclide with a long enough half life for easy preparation and shipping of the finished product, is gaining attention.

G.5. Radiation Oncology

108. The major advance in the field of radiotherapy in recent years has been the discovery through several high-quality clinical trials that the addition of pharmaceutical agents to radiotherapy improves the survival of patients with many common cancers such as lung, cervical, breast, head and neck, stomach, rectum, brain and prostate. However, in some cases this comes at the price of greater toxicity. Research continues in an attempt to modify the pharmaceutical agents and their target molecules in ways that will preserve their radio-sensitizing effect on the cancerous tissues, while decreasing the toxicity to the healthy tissues. Research is also being carried out into monitoring the delayed toxicity of chemical modifiers on the effects of radiation, as well as identifying target molecules that help cancer cells escape death after irradiation, and targets that are responsible for radiation injury in healthy tissues.

109. The last two decades have witnessed a continuing development in brachytherapy, which consists of placing sealed radioactive sources very close to or in contact with the target tissue. With this modality, high radiation doses can be delivered safely to a localized target volume over a short time. Newer high dose rate (HDR) sources, remote-control technology, surgical techniques and treatment planning software have contributed to a rapid development of this effective treatment modality. In particular, the recent development of HDR cobalt-60 sources may allow modern HDR brachytherapy to be performed with replacement of the sources needed less frequently than with other sources.

H. WATER AND THE ENVIRONMENT

H.1. Water Resources

H.1.1. Isotope Hydrology Techniques

110. Groundwater management is a key issue for sustainable human development, especially in semi-arid and arid regions. The increasing demand for water and the limited availability (and in many cases, quality) of surface water resources has led to the rapid development of groundwater for water supply, irrigation and industrial uses. For rational planning, an adequate understanding of the aquifer properties (origin of groundwater, recharge and renewal rates, vulnerability to pollution and interconnections between water bodies) is a pre-requisite to establishing sound development strategies.

111. The Agency has embarked on an effort to compile and disseminate isotope data from aquifers and rivers worldwide. These data are also being used to build thematic maps of fossil water aimed at assisting decision-makers in adopting better practices for groundwater management.

112. The development of a dual-inlet gas-source mass spectrometer in the 1950s heralded an explosive growth in the use of isotopes in hydrology and geology. New technological developments for isotope analysis of hydrological samples hold a great promise for revolutionizing the use of isotopes in water resources management. A portable instrument based on a laser technique has become available for use on the bench-top or in the field. This relatively inexpensive, low-skill and low-cost instrument, compared to the dual-inlet mass spectrometer, may be operated at a minimal operational cost by researchers and practitioners alike, and would overcome the present barrier to a wider use of isotopes in hydrology posed by a lack of easy availability of isotope analysis. The use of the laser isotope machine could result in a large number of isotope measurements worldwide, which would help to provide the necessary information to address some key hydrogeological challenges, such as the understanding and management of aquifer recharge, identifying groundwater flow patterns or establishing the relationships between surface and ground waters.

H.1.2. Desalination

113. There is continuing progress in using nuclear energy to desalinate seawater, driven by the expanding global demand for fresh water and by developments in small and medium sized reactors that may be more suitable for desalination than large power reactors. In the field of nuclear desalination, Japan has accumulated over 143 reactor-years of experience and Kazakhstan accumulated 26 reactor-years before shutting down the Aktau fast reactor in 1999.

114. India is proceeding with the full commissioning of the nuclear desalination demonstration plant at Kalpakkam, at which desalination using reverse osmosis (RO) has been in operation for several years and desalination using the multi-stage flash process is scheduled to start in 2006. In 2004, India

commissioned a low temperature evaporation plant at the CIRUS heavy water research reactor at Trombay utilizing its moderator waste heat for producing high quality water from seawater. In 2005, the Korea Atomic Energy Research Institute (KAERI) applied for a construction permit for a one-fifth scale, 65 MW(th) prototype of a System-Integrated Modular Advanced Reactor (SMART) with a desalination unit. Pakistan has begun construction on coupling a multi-stage distillation plant with the existing pressurized heavy water reactor at the Karachi nuclear power plant for demonstration purposes. In China, a test system is being set up in the Institute of Nuclear and New Energy Technology for validating the thermal-hydraulic parameters of a multi-effect distillation process. In Egypt, construction of the pre-heat RO test facility is scheduled for completion in 2006.

H.2. Environment

H.2.1. Demining

115. The investigations on the applicability of nuclear techniques for the detection of explosives including landmines have shown that targets smaller than 100 g cannot be detected with adequate reliability, especially in wet or damp conditions, and that the neutron backscatter based technique is of utility for arid zones alone, because it is the hydrogen component in the explosive that is detected. It has been difficult to identify any single nuclear technique as being superior or as the first line of inspection. The nuclear techniques are more likely to serve as ‘confirmatory’, after initial identification of a non-specific suspect sample/area. For the latter, one also requires some non-nuclear techniques. Accordingly, further research is being pursued to develop application of a combination of techniques and involving neutrons of different energies (as also suitable neutron sources for field applications) by a number of groups from both developed and developing countries under the Agency’s coordination.

H.2.2. Radionuclide Tracers for Ocean Circulation and Climate Coupling

116. Oceanic circulation is one of the key processes that control our climate. The ability to use radionuclides as tracers for oceanic processes is to a large extent driven by recent advances in clean sampling and analytical techniques as well as high precision mass spectrometry measurements. These techniques have been one of the stimuli of the recently implemented international research programme GEOTRACES which aims to coordinate research on oceanic cycling of trace elements and their isotopes. It is expected that this programme will significantly boost understanding of oceanic radionuclide behaviour.

H.2.3. Bioaccumulation in Marine Food Chains

117. Radionuclides and metals can be accumulated by aquatic organisms and magnified in concentration if the excretion is less than the uptake, a process called bioaccumulation, and which can give a contaminant a greater potential for toxicity in the food chain. Some studies have shown that bioaccumulation may occur for toxic radionuclide and metal contaminants, such as polonium, selenium, zinc and cadmium. It appears that metals that are bound to proteins in biota seem more likely to be bioaccumulated, but as yet there is still no systematic assessment available to evaluate bioaccumulation of various metals in marine food chains. Using radiotracers, the Agency’s Marine Environment Laboratory has commenced investigations into a range of metals to measure their potential to bioaccumulate in different marine food chains.

H.2.4. Unravelling Carbon Cycles with Compound-specific Isotope Analysis

118. The oceans contain 50 times the quantity of carbon dioxide (CO_2) found in the atmosphere and each year draw down 30–40% of the CO_2 generated from the burning of fossil fuels by humans. The

oceans thus play a pivotal role in the global carbon mass balance. Carbon isotopes (carbon-14 and carbon-13) have enabled geochemists to track global CO_2 cycles and such techniques will be valuable in assessing future mitigation options. Isotope chemists have succeeded in miniaturizing and merging these carbon isotope techniques into gas chromatography-isotope ratio mass spectrometry (GC-IRMS), making possible the analyses of carbon isotope ratios in less than a millionth of a gram of organic compound, enabling the identification of many more sources, pathways and fates of organic compounds and pollutants found in the environment.