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Nuclear Technology Review — Update 2005

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 is such an update, highlighting notable developments principally in 2004.
- The *Nuclear Technology Review — Update 2005* reviews the following areas: atomic and nuclear data, power applications, nuclear techniques in food and agriculture, human health, water resources, marine and terrestrial environments, research reactor utilization, accelerator utilization and industrial process monitoring.
- Information on the IAEA's activities related to nuclear science and technology can be found in the IAEA's *Annual Report 2004* (GC(49)/5), in particular the Technology section, and the *Technical Cooperation Report for 2004* (GC(49)/INF/2).
- 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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Executive Summary

1. The year 2004 marked the 50th anniversary of civilian nuclear power generation. While the current outlook for nuclear energy remains mixed, there is clearly a sense of rising expectations. Both the OECD International Energy Agency and the IAEA adjusted their medium-term projections for nuclear power upwards. The IAEA now projects 423–592 GW(e) of nuclear power installed worldwide in 2030, compared to 366 GW(e) at the end of 2004. This is driven by nuclear power's performance record, by growing energy needs around the world coupled with rising oil and natural gas prices, by new environmental constraints including entry-into-force of the Kyoto Protocol, by concerns about energy supply security in a number of countries, and by ambitious expansion plans in several key countries.

2. Asia accounted for 18 of the 26 reactors under construction at the end of the year, and for 20 of the last 30 reactors to have been connected to the grid. Excavation work began for Olkiluoto-3 in Finland, which will be the first new construction in Western Europe since 1991, and Electricité de France selected a site at Flamanville for a demonstration European PWR, with construction expected to begin in 2007. The US Nuclear Regulatory Commission approved 11 more licence extensions of 20 years each (for a total licensed life of 60 years for each plant). As part of the country's Nuclear Power 2010 programme, the US Department of Energy is sharing costs with two investor consortia preparing applications to test a new streamlined licensing process.

3. Nuclear power's share of global electricity generation held steady at 16%, indicating nuclear generation continued for the eighteenth year in a row to grow at the same pace as overall global electricity use. The number of new plants connected to the grid, five, exactly balanced the number retired, although the additions totaled 4785 MW(e) and the retirees only 1385 MW(e). Additionally, one laid-up plant was reconnected to the grid in Canada. However, there were only two new construction starts in 2004, and in accordance with existing nuclear phase-out policies, the Obrigheim reactor in Germany, and Barsebäck-2 in Sweden, were shut down in May 2005.

4. Uranium prices, which had been low and stable for the previous decade and a half, continued their climb — from $25/kg in 2002 to $75/kg on 29 June 2005. 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.

5. As of the end of 2004, six nuclear power plants had been completely decommissioned, with the sites released for unconditional use. Seventeen had been partially dismantled and safely enclosed, 33 were being dismantled prior to eventual site release, and 30 were undergoing minimum dismantling prior to long term enclosure. A new category of radioactive waste — very low level waste (VLLW) — has been introduced in some countries for very low radioactivity decommissioning waste that requires

less special treatment than traditional low level waste and thus has a much lower disposal cost. A VLLW repository — opened at Morvilliers, in France, in 2003 — reached full operation in 2004.

6. 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. Detailed geological investigations, which began in Sweden in 2002 at two candidate sites, are proceeding rapidly together with public consultations. The preparatory work in the USA for a licence application is well advanced.

7. National research on advanced reactor designs continues on all reactor categories — water cooled, gas cooled, liquid metal cooled, and hybrid systems. Five members of the US-initiated 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 23 members. It completed a series of case studies testing its assessment methodology and the final report on the updated INPRO methodology was published in December.

8. The realization of the International Thermonuclear Experimental Reactor, ITER, came closer with the announcement on 28 June 2005 by the ITER parties — China, European Union, Japan, Republic of Korea, Russian Federation and USA — that it will be sited at Cadarache in France. The aim of ITER is to demonstrate the scientific and technological feasibility of fusion energy by constructing a functional fusion power plant. ITER is expected to take about 8 years to build and will then operate for a further twenty years. It will be the first device in the world where a controlled nuclear fusion reaction will generate at least 5 times more power than it consumes. ITER will open new horizons for nuclear science and technology for energy applications, with expected spin-offs in many other areas.

9. Nuclear technology developments are rapid and cover many fields of application. Not all can be covered in this update review, but certain key areas and trends are covered where these are seen to be of significant interest to IAEA Member States, and which are of relevance to and have a role in helping to meet the Millennium Development Goals and addressing the WEHAB issues (water, energy, health, agriculture and biodiversity) identified at the Johannesburg World Summit on Sustainable Development in 2002.

10. With agriculture accounting for 70% of global water use, the application of multiple stable isotopes to assess water use efficiency in a range of cropping and water irrigation systems, including, for example, investigations into the influence of water irrigation scheduling on fertiliser use efficiency are doubly beneficial for the provision of both food and water. Mutation induction breeding for the identification of improved varieties of crops that are water-use efficient and adaptable to growth in harsh environments contributes to increasing the efficiency of use of scant water resources. Water resource management also shows a growing focus on management of transboundary aquifers, using isotopic tools for defining water movement, water age, and determining sources of pollution.

11. In human health, short-lived radionuclides are assisting clinicians to study metabolic processes. One of the fastest growing techniques is positron emission tomography (PET), using ultra short-lived radioisotopes attached to biological markers, which when fused with X-ray computed images provides an even more powerful tool for health monitoring and diagnoses. New challenges are evolving in radiotherapy with the introduction of image guided radiotherapy techniques, which have the capability to track and maintain beam accuracy following changes in tumour and patient position.

12. In the marine environment, new insights into climate change are expected from research using isotopic studies into the El Niño Southern Oscillation phenomenon. Increasing recognition is given to the oceans' ability to absorb carbon dioxide, and thus to their influence on the climate. Studies using

thorium-234, naturally derived from uranium-238 in seawater, are assisting oceanographers to better understand the oceans' role in this area. Understanding of the radioecology of the terrestrial environment is also being assisted through nuclear instrumentation, for example through developments in remote sensing using airborne gamma ray surveys.

13. Research reactors and accelerators continue to find new uses. Research reactor produced radioisotopes are in extensive use in medicine and industry, and neutron beams from research reactors are providing powerful probes into a variety of applications that make use of neutron scattering and radiography techniques. Accelerator based nuclear techniques appear promising for the development of novel materials, while accelerator mass spectrometry is exciting interest in carbon-14 dating techniques, drug research and environmental monitoring.

A. Atomic and Nuclear Data

14. Atomic and nuclear data continue to provide the fundamental basis for planning and designing reactors, for plant operations and safety upgrades, as well as for facilitating decommissioning activities in nuclear facilities. Significant technological developments include both the IAEA's nuclear database customer services and the preparation of better atomic and nuclear physics databases. The links with other major data network centres, such as the United States National Nuclear Data Center (NNDC) and the Nuclear Energy Agency (NEA), remain extremely fruitful. The preparedness to meet international needs for easy, reliable, platform-independent access to quality nuclear data is increasing, especially encouraged by the development of the Internet and information technology tools.

15. Significant benefits were judged to result from moving the IAEA's nuclear databases and services to other communication platforms. This joint effort undertaken in conjunction with the NNDC led to the completion of the extensive first stage in mid-2004. Modern software and hardware technologies have been tested and installed to enable new and more ambitious modernization approaches, and have resulted in the development of multi-platform nuclear data systems with a higher level of accessibility and reliability for end users. Further improvements have been identified and are proposed for implementation in 2005.

16. Continuing advances in the compilation and evaluation of atomic and molecular data support not only the International Thermonuclear Experimental Reactor (ITER) project, but also other research and technology pursuits for inertial fusion confinement. The scope for closer cooperation and review of the data needs for supporting nuclear fusion research warrant global emphasis.

17. Medical applications of radiation are growing, and reliable data, for both efficacious, safe treatment planning as well as for optimal designs of the facilities themselves, are crucial to ensure the cost-effectiveness and widespread availability of the applications. A sound knowledge of these data is needed for the optimal production of such radioisotopes as fluorine-18, strontium-82 and iodine-123 to the required purity for safe medical application. Cancer incidence rates and the alarming rise expected in the coming years demand concerted efforts and strategies to tackle the disease, and appropriate supporting atomic and nuclear data to aid advances in promising treatment methods are strongly sought by radiation oncologists and medical physicists.

B. Power Applications

B.1. Nuclear Power Today[1]

18. Worldwide there were 440 nuclear power plants (NPPs) operating at the end of 2004. Over the course of the year, nuclear power supplied 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 18 years.

19. The global energy availability factor for NPPs climbed to approximately 83% in 2004, up from 81% in 2003. For comparison the global energy availability factor for NPPs was 76% a decade earlier, in 1994.

20. Table B-1 summarizes the status of nuclear power around the world as of 31 December 2004.

21. Five new NPPs were connected to the grid in 2004 (two in Ukraine and one each in China, Japan and the Russian Federation), and one laid-up plant was reconnected in Canada. This compares to two new grid connections (and, in Canada, two reconnections) in 2003 and six new grid connections in 2002.

22. There were five NPP retirements in 2004 — four 50 MW(e) units in the United Kingdom and the 1185 MW(e) Ignalina-1 reactor in Lithuania. This compares to six retirements in 2003 and four in 2002.

23. Using the IAEA's definition that construction begins with the first pouring of concrete, construction began on two NPPs in 2004, India's 500 MW(e) prototype fast breeder reactor and Japan's 866 MW(e) Tomari-3 PWR. In addition, active construction resumed on two NPPs in the Russian Federation, Kalinin-4 and Balakovo-5, whose previous classification had been 'construction suspended'. Also site preparation began in Finland for the 1600 MW(e) Olkiluoto-3 plant. There had been one construction start in 2003 and seven in 2002.

24. Current expansion, as well as near-term and long-term growth prospects, is centred in Asia. As shown in Table B-1, of 26 reactors under construction worldwide[2] at the end of 2004, 17 were located either in China, the Republic of Korea, Japan or India. Twenty of the last 30 reactors to have been connected to the grid were in the Far East and South Asia.

25. Within Asia, capacity is greatest in Japan, with 54 reactors in operation and three under construction. By the end of 2004, TEPCO had returned to service 16 of the 17 reactors shut down in 2002. This boosted nuclear power's share of Japanese electricity to 29.3% in 2004 as shown in Table B-1, up from the 2003 value of 25%, but still below the 34% share enjoyed in 2002 and 2001.

26. In the Republic of Korea, with 19 reactors in operation and one under construction, 38% of total electricity came from nuclear power in 2004.

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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/Anrep2004/index.html) and on the IAEA web site 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).

[2] The total includes also Taiwan, China.

Table B-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 31 December 2004)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2004		Total Operating Experience	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	7.3	8.2	52	7
ARMENIA	1	376			2.2	38.8	37	3
BELGIUM	7	5 801			44.9	55.1	198	7
BRAZIL	2	1 901			11.5	3.0	27	2
BULGARIA	4	2 722			15.6	41.6	133	2
CANADA	17	12 113			85.3	15.0	509	7
CHINA	9	6 602	2	2 000	47.8	2.2	47	11
CZECH REPUBLIC	6	3 548			26.3	31.2	80	10
FINLAND	4	2 656			21.8	26.6	103	4
FRANCE	59	63 363			426.8	78.1	1 405	2
GERMANY	18	20 679			158.4	31.8	666	0
HUNGARY	4	1 755			11.2	33.8	78	2
INDIA	14	2 550	9	4 092	15.0	2.8	237	5
IRAN, ISLAMIC REPUBLIC OF			1	915				
JAPAN	54	45 468	3	3 237	273.8	29.3	1 176	4
KOREA, REPUBLIC OF	19	15 850	1	960	124.0	38.0	239	8
LITHUANIA	1	1 185			13.9	72.1	38	6
MEXICO	2	1 310			10.6	5.2	25	11
NETHERLANDS	1	449			3.6	3.8	60	0
PAKISTAN	2	425			1.9	2.4	37	10
ROMANIA	1	655	1	655	5.1	10.1	8	6
RUSSIAN FEDERATION	31	21 743	4	3 775	133.0	15.6	791	5
SLOVAKIA	6	2 442			15.6	55.2	106	6
SLOVENIA	1	656			5.2	38.9	23	3
SOUTH AFRICA	2	1 800			14.3	6.6	40	3
SPAIN	9	7 585			60.9	22.9	228	2
SWEDEN	11	9 469			75.0	51.8	322	1
SWITZERLAND	5	3 220			25.4	40.0	148	10
UKRAINE	15	13 107	2	1 900	81.1	51.1	293	6
UNITED KINGDOM	23	11 852			73.7	19.4	1 354	8
UNITED STATES OF AMERICA	104	99 210			788.6	20.0	2 975	8
Total[b]	440	366 311	26	20 826	2618.6	16%	11 588	6

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, 4884 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 37.9 TW·h of nuclear electricity generation, representing 20.9% of the total electricity generated in 2004;
— 140 years, 1 month of total operating experience.

27. Elsewhere in Asia, nuclear power's absolute and relative contributions are smaller, but China and India in particular plan significant expansion. India, with 14 operating reactors at the end of 2004, got 2.8% of its electricity from nuclear power. However, nine more reactors were under construction, including the 500 MW(e) prototype fast breeder reactor begun in 2004 at Kalpakkam, and India's current goal is to supply 25% of its electricity from nuclear power by 2050.

28. China, with nine operating reactors at the end of 2004, two under construction and 2.2% of its electricity from nuclear power, plans expansion to 32-40 GW(e) by 2020 for 4-5% of the electricity supply. In 2004 China's State Council formally approved at least 7 GW(e) of new capacity beyond that already under construction.

29. With the connection of Kalinin-3 to the grid in December 2004 and the resumption of active construction on Kalinin-4 and Balakovo-5, the Russian Federation had 31 reactors in operation at the end of the year and 4 more under construction. Ukraine, with the connections of Khmelnitski-2 and Rovno-4 to the grid, had 15 reactors in operation and 2 under construction. The only other current construction in Eastern Europe is Cernavoda-2 in Romania. As mentioned above, Ignalina-1 in Lithuania was retired at the end of 2004.

30. Western Europe had 137 NPPs operating at the end of 2004, down from 148 in 2001 due mainly to the retirement in the UK of ten small units from the 1950s and 1960s (eight 50 MW(e) units and two 123 MW(e) units). There is no current construction of NPPs in Western Europe, but excavation work began in 2004 for Olkiluoto-3 in Finland. Also, following the French Parliament's adoption of necessary legislation, Electricité de France selected a site for a demonstration European pressurized water reactor (EPR), with construction expected to start in 2007. These two plants will be the first EPRs to be built. France has started down the route of 'replacing nuclear with nuclear' in connection with ageing NPPs built in the 1970s and 1980s. As for the UK, the 2003 White Paper on energy policy does not propose new NPPs, citing their expense and unresolved waste issues, but leaves the nuclear option open in case at some point new nuclear capacity becomes necessary.

31. In the United States of America, the Nuclear Regulatory Commission (NRC) approved eleven more licence extensions of 20 years each (for a total licensed life of 60 years for each NPP), bringing the total number of approved licence extensions to 30 by the end of the year. Approximately three quarters of the USA's 104 NPPs have either received, applied for, or stated their intention to apply for such licence extensions. The US Department of Energy (DOE) approved financial assistance to two industry consortia for nuclear power plant licensing demonstration projects taking advantage of the NRC's new Combined License (COL). Such assistance is part of the USA's Nuclear Power 2010 programme to deploy new nuclear capacity by 2010.

32. In Canada, near-term expansion of nuclear generation is taking the form of restarting some or all of the 8 nuclear units (out of a Canadian total of 22) that have been shut in recent years. The first two such restarts took place in 2003. A third, at Bruce A-3, took place in 2004, and the authorities of the province of Ontario have approved Ontario Power Generation's plan to restart Pickering A-1.

33. In Latin America there are two operating plants in each of Argentina, Brazil and Mexico, and one under construction in Argentina.

34. There are two operating plants in South Africa.

B.2. The Future

B.2.1. Updated medium-term projections[3]

35. Each year the IAEA publishes updated medium-term nuclear energy projections. The 2004 updates are shown in Figure B-1, along with an updated reference scenario from the OECD International Energy Agency's (IEA's) *World Energy Outlook 2004*. In the figure, the left bar in each triplet is the IAEA's low projection, which 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. The low projection is labelled with the suffix 'L', and shows the breakdown of nuclear production by region.

36. The middle bar in each triplet is the IAEA's high projection, which incorporates additional reasonable planned and proposed nuclear projects beyond those already firmly in the pipeline. The bars for the high projection are labelled with the suffix 'H' and also show the breakdown by region.

37. For comparison, the bar on the right in each triplet shows the updated reference scenario of the IEA's *World Energy Outlook 2004*. The IEA's reference scenario, which is updated every other year, is a well-known and frequently cited reference point in international deliberations on energy policies and markets. It is built on essentially the same approach as the IAEA low projection. The largest share of the quantitative differences between the two in Figure B-1 comes from lower IEA projections for Eastern Europe.

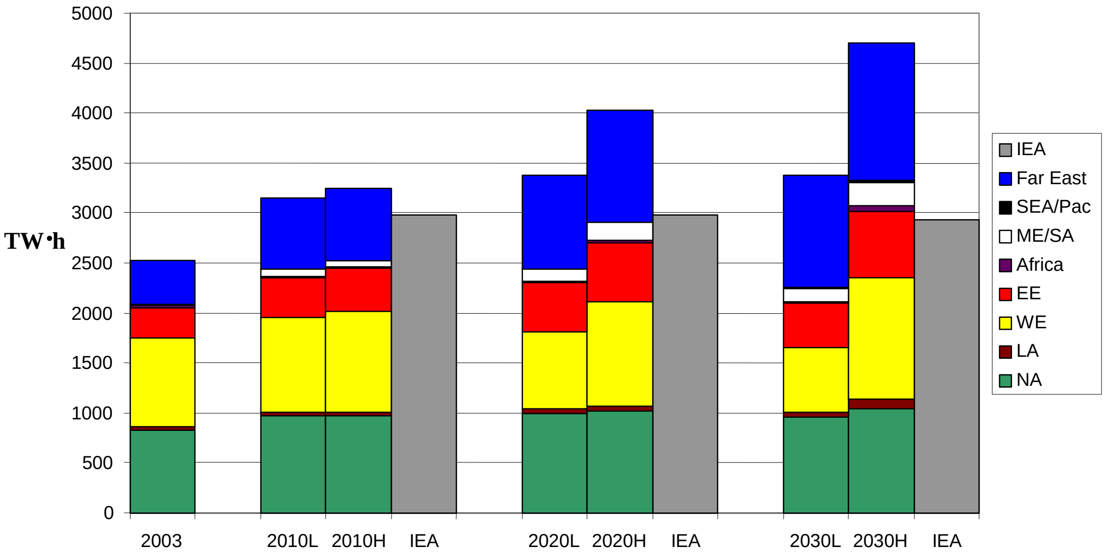

Figure B-1. Global electricity generation from nuclear power in 2003 and in three projections through 2030 (NA, North America; LA, Latin America; WE, Western Europe; EE: Eastern Europe; ME/SA: Middle East/South Asia; SEA/Pac: Southeast Asia/Pacific).

38. The IAEA's low projection projects nuclear generation in 2030 of 3379 TW·h, a 34% increase in nuclear production relative to 2003. Significantly, the IAEA's low projections have been revised

[3] More detail on recent IAEA projections is available at http://nesisda2/rds-1/. The IAEA'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/Anrep2004/index.html) and on its web site at http://www.iaea.org/OurWork/ST/NE/Pess/.

upwards every year since 2000. The 3378 TW·h shown in Figure B-1 for 2020 is 60% higher than the 2020 value that the IAEA was projecting in 2000. (The IAEA projections in 2000 only looked ahead as far as 2020.)

39. The IAEA's high projection shows an 86% increase in nuclear electricity production between 2003 and 2030. There has been less change, and a less consistent pattern of change, in the high projections from year to year. Taken together the evolution of the projections makes sense for an industry that has reasonably good prospects, but is not growing dramatically. The list of reasonable medium-term projects at the high end is fairly stable, and each year more and more of them get promoted from promising prospects to actual projects in the pipeline.

40. Figure B-1 shows significant differences among different parts of the world. As noted earlier, expansion is centred in the Far East, where growth is greatest in all projections. There is significant expansion in Eastern Europe in both the IAEA's high and low projections but very modest growth in North America. In Western Europe there is a contraction in the low projection as NPP retirements outpace new construction, but a significant expansion in the high projection. Growth rates are high in the Middle East and South Asia in both IAEA projections, although the region starts from a small 2003 base.

41. Although Figure B-1 does not show the regional breakdown for the IEA reference scenario, which uses slightly different regions than does the IAEA, the underlying pattern is largely the same as in the IAEA low projection — expansion in the Far East and South Asia, contraction in Western Europe and stability in North America.

B.2.2. Sustainable development and climate change[4]

42. In the longer term, the future of nuclear power will depend inter alia on how well it helps meet growing global energy needs and relieves environmental burdens associated with energy use. With respect to growing global energy needs, there were no major international deliberations in 2004 on energy needs for sustainable development. The UN Commission on Sustainable Development will next take up energy in its fourteenth and fifteenth sessions in 2006 and 2007.

43. With respect to environmental protection, the major global development in 2004 came in November with ratification by the Russian Federation of the Kyoto Protocol to the United Nations Framework Convention on Climate Change. As a result, Annex I countries[5] ratifying the protocol collectively accounted for more than 55% of 1990 Annex I carbon dioxide emissions, and the Protocol entered into force 90 days later on 16 February 2005.

44. Entry into force of the Kyoto Protocol will likely have little immediate effect on nuclear expansion. The protocol covers only the first commitment period, 2008–2012, and different countries have adopted different policies to meet their Kyoto Protocol limits. Not all these policies benefit nuclear power, despite its very low greenhouse gas (GHG) emissions — only 2–6 grams of carbon per kilowatt-hour for the full nuclear fuel chain, about the same as wind and solar power. But in the longer run, the expectation is that progress toward a 'carbon constrained' economy should make nuclear power increasingly attractive. In the past its advantage of minimal GHG emissions has been invisible to investors, as the lack of restrictions or taxes on GHG emissions meant there was no economic value

[4] 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/Anrep2004/index.html) and on the IAEA website at http://www.iaea.org/OurWork/ST/NE/Pess/climate.shtml.

[5] The Annex I countries are the OECD countries as of 1992 plus countries with economies then in transition.

to their avoidance. The Kyoto Protocol is currently the only operative route toward widespread, coordinated restrictions on GHG emissions and thus an important step towards attaching a tangible economic value to nuclear power's avoidance of GHG emissions.

B.2.3. Current issues

Economics

45. Well run existing NPPs continue to be a generally competitive profitable source of electricity, as evidenced by the continued pace of licence extensions in the USA and elsewhere, although licence extensions outside the USA are generally for shorter periods and more frequent, or take the form of 'rolling extensions'.

46. For new construction, the competitiveness of nuclear power depends on, among other things, the costs of alternatives with which it must compete, the perspectives of investors, and the energy and electricity markets in which it will operate. As presented in Table B-2, recent estimates of the costs of new nuclear power plants and their principal competitors show ranges that reflect different technologies, national resource situations and investor perspectives. Table B-2's range spans two recently reported estimates reflecting current experience. Atomic Energy of Canada Limited has estimated the costs of completing Qinshan 3-1 and Qinshan 3-2 in Zhejiang, China, at $1500 per kW(e) (or 1163 euros per kW(e) based on the exchange rate used in Table B-2), and the price reported for the Olkiluoto-3 EPR is 1920 euros per kW(e).

47. Two important continuing trends in electricity markets in 2004 were towards increasing liberalization, and stricter limits on GHG emissions. The electricity market of the 15 member states of the European Union (prior to EU enlargement in 2004), for example, was fully opened for non-household customers in 2004, and in Japan 40% of the entire power market was opened during 2004 (to be increased to 60% in 2005). Also, an EU directive issued in October 2003 established the European Union Emission Trading Scheme for carbon dioxide emissions effective 1 January 2005, and national allocation plans (NAPs) to set initial emission allowances for installations were developed in the course of 2004. By the end of the year, the European Commission (EC) had completed assessments of 21 NAPs. It unconditionally approved 15 of the NAPs, conditionally approved 3 more, and 'partially rejected' the remaining 3.

Table B-2. Comparative costs estimates from recent studies

	MIT[a]	University of Chicago[b]	Royal Academy of Engineering[c]	DGEMP France[d]	METI Japan[e]	CERI Canada[f]	NEA/IEA[g]
Levelized Cost[g]	*euro cents/kWh*[h]	*euro cents/kWh*	*euro cents/kWh*	*euro cents/kWh*	*euro cents/kWh*	*euro cents/kWh*	*euro cents/kWh*
nuclear	5.2	3.2-5.5	3.3	2.8	3.8	3.4-5.8	1.6-5.3
coal	3.3	2.6-3.2	3.6-5.0	3.2-3.4	4.1	3.1-3.8	1.2-5.3
natural gas	2.9-4.3	2.7-3.5	3.1-4.0	3.5	4.5	4.7-4.9	2.9-5.0
oil					7.8		
hydropower							3.1-18.8
poultry litter			9.7				
onshore wind			5.3-7.7				2.4-11.2
offshore wind			7.9-10.3				4.0-9.5
wave/marine			9.4				
solar PV							9.4-145.4
Overnight Cost[i]	*euros/kW(e)*	*euros/kW(e)*	*euros/kW(e)*	*euros/kW(e)*	*euros/kW(e)*	*euros/kW(e)*	*euros/kW(e)*
nuclear	1550	930-1395	1642	1413	2026	1525-1931	832-1945
coal	1008	916-1132	1042-1171	1000-1100	1975	1040	557-1819
natural gas	388	388-543	428	505	1191	462	329-1001
oil					1953		
hydropower							1194-5413
poultry litter			2628				
onshore wind			1057				756-1266
offshore wind			1314				1269-2032
wave/marine			1999				
solar PV							2606-7877

a. The Massachusetts Institute of Technology, *The Future of Nuclear Power*, The Massachusetts Institute of Technology, Cambridge, Massachusetts, USA (2003)
b. The University of Chicago, *The Economic Future of Nuclear Power*, The University of Chicago, Chicago, Illinois, USA (2004)
c. The Royal Academy of Engineering, *The Cost of Generating Electricity*, London, UK (2004)
d. General Directorate for Energy and Raw Materials (DGEMP), French Ministry of the Economy, Finance and Industry, Paris, France (2003)
e. Ministry of Economy, Trade and Industry, Tokyo, Japan (2004)
f. 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
g. Nuclear Energy Agency and International Energy Agency, *Projected Costs of Generating Electricity: 2005 Update*, Organisation for Economic Co-operation and Development, Paris, 2005
h. The levelized cost of electricity is the price at the busbar needed to cover the operating plus annualized capital costs of a power plant.
i. National currencies used in the different studies are converted to euros using exchange rates quoted on 11 November 2004.
j. The overnight cost is the amount that would be paid out if all capital expenses occurred simultaneously. It includes no interest charges.

Safety[6]

48. 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 analyzing 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. Regular meetings of the IAEA/NEA Joint Incident Reporting System are one part of this global exchange process, where recent incidents can be discussed and analysed in detail.

49. Because of such information exchange and analysis, among other reasons, the nuclear industry's overall safety record continues to improve. World Association of Nuclear Operators statistics for 2003 show a low stable rate of unplanned automatic scrams at about one third the level at the beginning of the 1990s, and a continuing decrease in the already low industrial accident rate.

50. More detailed safety information and recent developments related to all nuclear applications are presented in the IAEA's annual *Nuclear Safety Review*.

Decommissioning, spent fuel and waste[7]

51. For decommissioning, the trend towards immediate dismantling continues. In the USA one reason is to make use of available waste disposal sites while they are still open and before costs increase. NPPs nearing the end of the process include Yankee Rowe and Maine Yankee (both with decommissioning 90% complete at the end of 2004 and 'unrestricted release' planned for 2005), Big Rock Point (85% complete and unrestricted release also planned for 2005), Trojan (95% complete and licence termination planned for 2005) and Connecticut Yankee (unrestricted release planned for 2007). Exceptions to the immediate dismantling strategy include mostly multi-unit sites where dismantling is planned once all units have reached the end of their operating lifetimes.

52. Even where strategies are similar, reasons are often different for specific NPP situations. In Germany, for example, where immediate dismantling also appears to be the preferred approach, the large scale immediate dismantling project at the Greifswald site in eastern Germany (five reactors originally in operation, one nearing operation and two under construction) greatly facilitated the retention of key staff and the re-employment of a very large operational staff.

53. An important recent development is the introduction of a new category of radioactive waste in some countries — very low level waste (VLLW). A VLLW repository opened at Morvilliers, France in 2003 and reached full operation in 2004. Spain is also considering a VLLW repository. The VLLW category is intended to accommodate most decommissioning waste at a disposal cost much lower than that of traditional low level wastes.

54. With respect to spent fuel, inventories continue to grow. However, spent fuel has been safely stored for decades at reactors and interim storage sites, and with some modest expansion in storage, these on-site and interim facilities can provide needed storage for many years.

55. For high level waste, the most progress on disposal facilities has been made in Finland, Sweden and the USA. In Finland construction work began in 2004 on the underground laboratory at Olkiluoto that will be used to characterize the local geology and may later be incorporated into the final

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[6] 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/Anrep2004/index.html) and on the IAEA web site at http://www-ns.iaea.org/.

[7] More detailed information on the IAEA's activities on decommissioning, spent fuel and waste is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2004/index.html) and on the IAEA web site at http://www.iaea.org/OurWork/ST/NE/NEFW/index.html and http://www-ns.iaea.org/home/rtws.asp.

repository. Construction of the repository should start in 2011 and be in operation in 2020. Sweden has begun detailed geological investigations at two candidate sites. The Swedish Nuclear Fuel and Waste Management Company (SKB) hopes to make a final site proposal by about 2008. In the USA the Waste Isolation Pilot Plant in New Mexico began accepting military transuranic waste in 1999 for permanent disposal, and in 2002, the US Government decided to proceed with the Yucca Mountain disposal site. Operations at Yucca Mountain are planned to begin in 2010. The major development in 2004 was a court ruling that the regulations developed for the site by the Environmental Protection Agency are less stringent than required by law. If the decision stands, it will likely require changes in either the facility's design, or the law.

56. The 2002 Canadian Nuclear Fuel Waste Act sets a November 2005 deadline for Canada's Nuclear Waste Management Organization (NWMO) to recommend an approach to managing used nuclear fuel. In May 2005, the NWMO published draft recommendations for comment and review, proposing an 'adaptive phased' approach with three phases. First would be on-site storage of spent fuel at reactors for approximately 30 years. During this time a site for a centralized repository would be chosen and an underground research laboratory would be built. The second phase would also last approximately 30 years. Depending on "societal direction", used fuel could be moved to the central site for interim storage during this phase. In phase three, used fuel would be placed in the repository. Future generations would decide in phase three whether and when to close the repository, and what kind of post-closure monitoring would be required.

Nuclear technology and the non-proliferation of nuclear weapons[8]

57. Several developments in 2003 and 2004 heightened international awareness of the risk of nuclear weapons proliferation associated with the sensitive parts of the nuclear fuel cycle. A number of revelations concerning undeclared activities for uranium enrichment and reprocessing of spent fuel, as well as the discovery of the existence of an international illicit market in sensitive nuclear technologies underlined the need for improved controls over these parts of the nuclear fuel cycle. In response, a series of proposals have been developed, including those by the Director General of the IAEA, designed to enhance the nuclear non-proliferation regime through measures relating to strengthened safeguards, improved physical protection of nuclear material and facilities as well as bolstering the current system of nuclear export controls. In addition, work has continued in the framework of INPRO and the Generation IV initiative with respect to the development of future proliferation resistant nuclear power technologies.

[8] 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/Anrep2004/index.html) and on the IAEA web site at http://www.iaea.org/OurWork/SV/Safeguards/index.html.

B.2.4. Resources[9]

58. In 2004 the dramatic uranium dollar price increases that began in 2003 continued, as shown in Figure B-2. Contributing factors include production disruptions in several uranium mines, a weakened dollar, and the reduction of inventories and secondary supplies. The spot price mid-2005 reached $75/kg, compared to $40/kg at the beginning of 2004. In the medium term, demand increases are projected to put pressure on prices in both the IAEA high and low projections (Section B.2.1) and, at least through 2010, in the IEA reference scenario.

59. The latest update of the IAEA and OECD Nuclear Energy Agency's biennial 'Red Book', *Uranium 2003: Resources, Production and Demand*, published in 2004, reports uranium production of 36 042 tU in 2002, down somewhat from the 37 020 tU produced in 2001. In 2002 production provided about 54% of world reactor requirements (66 815 tU), with the remainder being met by secondary sources including civilian and military stockpiles, uranium reprocessing and re-enrichment of depleted uranium.

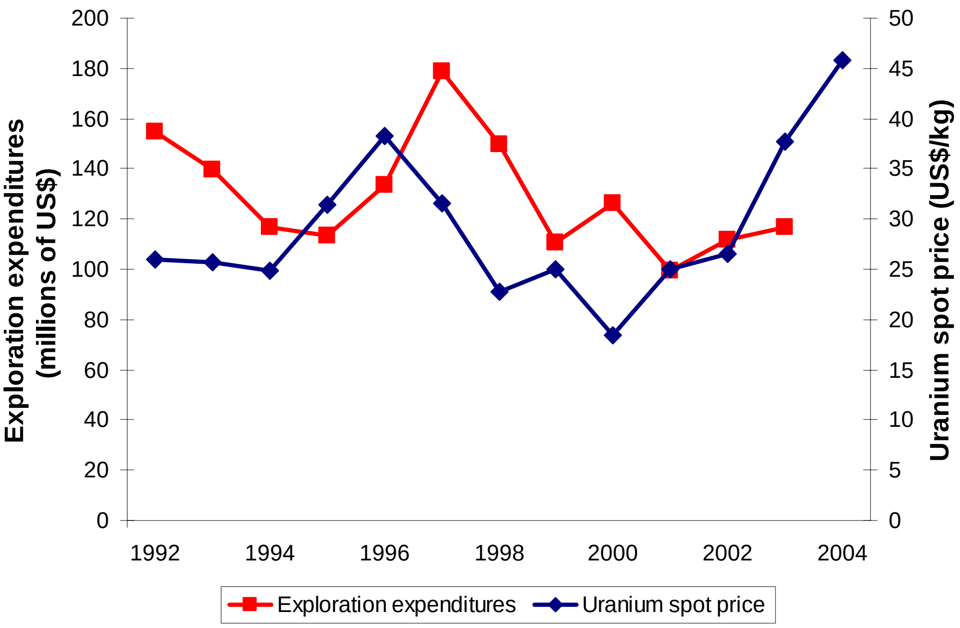

Figure B-2. Uranium market price and exploration expenditures, 1992–2004.

60. The uranium production decline since the early 1990s is not due exclusively to low prices. More stringent regulation and increasing attention to environmental concerns have also contributed. Lead times from discovery to production, for example, in Canada in the 1940s and 1950s were typically 3-10 years. In the 1960s and 1970s, 11–16 years was the norm, and the 2003 Red Book notes that lead times of the order of 10–20 years have become common in many countries since the 1980s.

61. Historically price hikes have usually been followed by increased uranium exploration a year or so later, as shown in Figure B-2. Indications are that these trends will continue, and the exploration expenditures line will be distinctly higher in 2004, when all the data are in.

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[9] More detailed information on IAEA activities concerning nuclear resources is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2004/index.html) and on the IAEA web site at http://www.iaea.org/OurWork/ST/NE/NEFW/nfcms_home.html.

B.2.5. Advanced fission and fusion[10]

62. In response to the challenges currently facing nuclear power as outlined in Section B.2.3, many countries are working to improve the economics, safety, waste management and proliferation resistance of advanced reactor-fuel cycle systems. For advanced NPP designs, efforts are focused on making plants simpler to operate, inspect, maintain and repair. In the near term, most new NPPs are likely to be evolutionary designs building on proven systems while incorporating technological advances and often economies of scale. For the longer term, the focus is on innovative designs, several of which are in the small-to-medium range (up to 700 MW(e)). These envision construction with factory-built components, including complete modular units for fast on-site installation, creating possible economies of series production instead of economies of scale. Some are being designed for operation without on-site refuelling. Other advantages foreseen for smaller units are easier financing, greater suitability for small electricity grids or remote locations, and their potential for district heating, seawater desalination and other non-electric applications. Such advances should increase their attractiveness for many developing countries and some industrialized countries.

63. Important design efforts on large evolutionary light water reactors (LWRs) are underway in China, France, Germany, Japan, the Republic of Korea, the Russian Federation and the USA. The main efforts on small and medium-size evolutionary LWR designs are being made in China, France, Japan, the Russian Federation and the USA. *Innovative* LWR designs (i.e. those that incorporate radical conceptual changes in design approaches or system configuration) are being developed in Argentina, Japan, the Republic of Korea, the Russian Federation and the USA.

64. Both Canada and India are working on advanced heavy water reactor designs, and advanced gas cooled reactor designs are being developed in China, France, Germany, Japan, the Russian Federation, South Africa, the UK and the USA. For liquid metal cooled fast reactors, development activities are underway in China, France, India, Japan, the Republic of Korea and the Russian Federation. Development activities for lead alloy and sodium liquid metal cooled fast reactor systems and for gas (helium) cooled fast reactors are being conducted within the Generation IV International Forum (GIF) and in the Russian Federation. Research on fast neutron spectrum hybrid systems (e.g. accelerator driven systems) is underway in India, the Republic of Korea, Japan, the Russian Federation, the USA and eight EU countries.

65. Complementing the many initiatives above are two major international efforts to promote innovation — GIF and the IAEA’s International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). Members of GIF are Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the UK, the USA and Euratom. 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.

66. Members of the IAEA’s INPRO project are Argentina, Armenia, Brazil, Bulgaria, Canada, Chile, China, the Czech Republic, France, Germany, India, Indonesia, the Republic of Korea, Morocco, the Netherlands, Pakistan, the Russian Federation, South Africa, Spain, Switzerland, Turkey, Ukraine and the European Commission. INPRO published an initial report in 2003 that outlined the potential of nuclear power and specified guidelines and a methodology for evaluating innovative concepts. In 2004

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[10] More detailed information on IAEA activities on advanced fission is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2004/index.html) and on the IAEA web site at http://www.iaea.org/OurWork/ST/NE/NENP/NPTDS.html. Information on IAEA activities on fusion is also available in the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2004/index.html).

this methodology was tested through pilot applications in a series of case studies, and a final report on the updated INPRO methodology was published in December. The next stage of INPRO is to facilitate assessments of innovative nuclear energy systems (INSs) by Member States using the updated INPRO methodology, to define and model INS deployment scenarios taking into account strategies considered by Member States, and to identify possible frameworks and implementation options for collaborative R&D for INS development which could be performed during the next phase.

67. Much of the current experimental and theoretical research on nuclear fusion is focused on the International Thermonuclear Experimental Reactor (ITER). ITER's 'engineering design activities' stage has been completed, and the realization of ITER came closer with the announcement on 28 June 2005 by the ITER parties — China, European Union, Japan, Republic of Korea, Russian Federation and USA — that it will be sited at Cadarache in France. The aim of ITER is to demonstrate the scientific and technological feasibility of fusion energy by constructing a functional fusion power plant. ITER would take about 8 years to build and will then operate for a further twenty years. It will be the first device in the world where a controlled nuclear fusion reaction will generate at least 5 times more power than it consumes. ITER will open new horizons for nuclear science and technology for energy applications, with expected spin-offs in many other areas.

68. Research also continues on other magnetic confinement approaches, and inertial confinement is being developed intensively by national programmes in France and the USA. The National Ignition Facility in the USA is scheduled for completion in 2008. Information on IAEA sponsored research concerning fusion and other topics can be found at http://www-crp.iaea.org, in the report *Coordinated Research Activities: Annual Report and Statistics for 2004.*

C. Nuclear Techniques in Food and Agriculture

C.1. Sustainable Land Management and Water-Use Efficiency

69. The increasing demand for food worldwide has placed tremendous pressure on the sustainability of land and water resources and moved the research agenda on farming systems from one of simply identifying ways of increasing production to developing options for doing this without degrading natural resources. This evolution of the research agenda has brought with it both new challenges to applying existing nuclear techniques, and new applications to tackle issues relating to environmental sustainability. One of the major challenges is how to apply nuclear techniques to soil and water conservation issues at the wider ecosystem, watershed and landscape levels rather than simply at the plot and field level; yet another is how to identify crops that are efficient at utilizing water and soil nutrient resources and are adapted to harsh environments (e.g. drought, salinity or nutritional stress). A wide range of nuclear techniques are currently being explored to diagnose unsustainable practices and identify management practices at farm and wider eco-system scales. These include phosphorus-32 and nitrogen-15 isotopic tracers, variations in natural abundance of stable isotopes (such as carbon-13, oxygen-18 and nitrogen-15) in soil, plants and water, and fallout radionuclides (caesium-137, lead-210 and beryllium-7). In response to increasing concerns about water quantity and quality, new initiatives are being undertaken globally, based on recent advances in the use of multiple stable isotopes (hydrogen-2, oxygen-18, carbon-13 and nitrogen-15) to assess water-use efficiency in a range of cropping and water irrigation systems. These will include initiatives on the influence of water irrigation scheduling on fertiliser-use efficiency, the efficient re-use of agricultural wastewaters as a source of water and nutrients for crop productivity, and the relative importance of different sources of pollutants from agricultural land in water runoff. The above-mentioned isotopes together with the use

of non-isotopic tracers and soil moisture neutron probes should provide information that helps to develop farm management tools to enhance water-use efficiency and sustainable farming systems in both rain-fed and irrigated land through a better understanding of soil–plant–water relationships.

C.2. Crop Improvement

70. Mutation induction coupled to selection remains the most ‘clean’ and inexpensive way to create varieties by changing single characteristics without touching the general phenotype. Controversies focusing on the potential hazards and risks of spreading and consuming genetically modified (GM) organisms are causing many countries to debate whether to allow the growing of GM crops and consumption of GM products. Against this background, both commercial companies and the public sector are showing renewed interest in mutation induction techniques as an alternative to transgenics. More than 60% of mutant varieties were released after 1985 in the era of transgenics in plant breeding (89% of the officially released mutant varieties are radiation-induced mutant varieties). This is also due to the major economic successes of mutagenesis-enhanced breeding in the USA (rice, barley, sunflower, grapefruit, peppermint); Pakistan (cotton); India (blackgram); Australia and Canada (linseed); Japan (pear); and China and Australia (rice).

71. Another major trend is the increased privatization of research in mutation-induction breeding programmes, not only for ornamental flowers, but also for industrial, cash and food crops. This is well documented by the increase of queries to the public FAO/IAEA Mutant Varieties Database (MVD) and the FAO/IAEA Mutant Germplasm Repository (MGR) database. Information about the protocols used to induce mutations in different crops has become increasingly privileged (trade secret), and less information about the mutant origin of varieties is publicly available (see Fig. C-1).

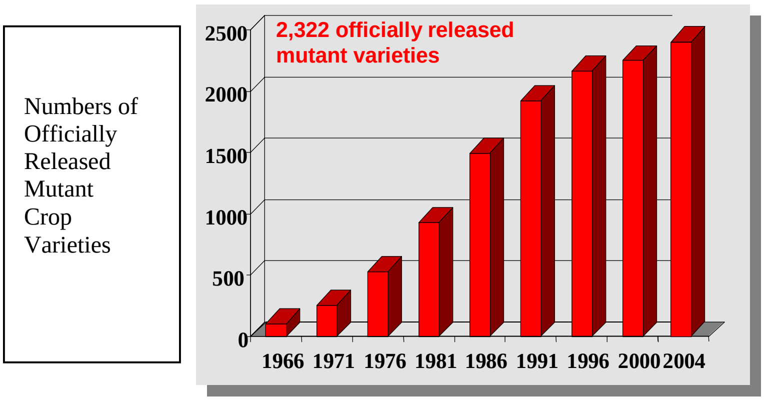

Figure C-1. Cumulative number of officially released varieties in the MVD. Information received from the official national authorities of FAO and IAEA Member States.

72. Predicting what may be available or important in the future and the likely consequences is difficult, but recent developments in biotechnology — especially in understanding the structure and function of plant genomes — confirms mutation induction as one of the most efficient and cost-effective tools for functional genomics projects dealing with gene discovery and revealing gene function. The need to organize extended mutant collections for the investigation of basic developmental, biochemical and physiological mechanisms is voiced more and more urgently, culminating in the development of mutation grids (collections of fully characterized and selected mutants arrayed for high throughput analyses) for functional genomics. High throughput technologies and functional genomic methodologies will open up new angles to look at fundamental and applied

aspects of biology. The shift will be from the static view of genome fingerprinting to the dynamic view of transcriptome (all the expressed genes) profiling. Nuclear techniques are increasingly fostering the development of this paradigm shift by producing the basic and necessary mutant resources.

C.3. Crop Protection

73. The interest of commercial companies in the mass production of sterile insects for the integrated application of the sterile insect technique (SIT), especially to combat fruit fly pests, and in particular the Mediterranean fruit fly, is increasing. The SIT was previously mainly used for the local eradication of key insect pests. This did not lead to a predictable and continuous demand for sterile insects. However, at least for Mediterranean fruit fly, the SIT has now progressed to where it is a cost-effective technology. As a result, the SIT approach is shifting to the routine suppression rather than eradication of pest populations, leading to a continuous demand for sterile medflies and thus opening the door to the commercialization of the SIT for the Mediterranean fruit fly.

74. This development raises a number of legal and intellectual property right issues related to the SIT technology in use and under development. Previously, mostly governments were directly involved in the production and release of the sterile insects, sharing this technology freely, and hence these issues were largely absent. For example, one of the most important technologies has been the introduction of genetic sexing strains (GSS), such as the male-only medfly temperature sensitive lethal strains, into SIT programmes. These male-only strains are now used in all countries where medfly SIT programmes are being implemented, and the conditions of transferring or licensing them to private companies still need to be defined.

75. The use of sterile insects, instead of insecticides, to suppress the key pest, contributes to the survival and effectiveness of the biological control agents to control secondary pest problems, and thus impacts positively on the demand for these agents. Alone for the Mediterranean basin it is estimated that the potential demand for sterile Mediterranean fruit flies amounts to at least 4 billion sterile males per week, close to the total number currently being produced worldwide. In this region, mass-rearing facilities are under construction in Israel and in Spain to address part of this demand.

76. In Argentina, ten years of an integrated area-wide SIT programme against the Mediterranean fruit fly has recently culminated in Chile officially recognizing major commercial fruit producing areas in the province of Mendoza as ‘medfly-free’. This will enable agricultural products to be moved directly through Chile to ports on the Pacific Ocean for export to the fresh fruit markets in Pacific-rim countries.

77. Recent advances in the ability to create transgenic strains of pest insects open the possibility of using molecular approaches for SIT strain improvement. A number of universities and research organizations are currently evaluating and characterizing in secure laboratories several such strains with beneficial characters. Their deployment, however, even as sterile insects, requires considerable further risk-assessment and a regulatory framework, and thus is not foreseeable in the near future.

C.4. Improving Livestock Productivity and Health

78. The main efforts in livestock research involve the use of molecular and genetic methods to understand and manipulate genomes. Despite the increasing use of non-radioactive methods, radioisotopes are still being widely used in these efforts.

79. The potential for using nuclear technologies to the benefit of farmers in developing countries is highlighted in the recent proceedings of the FAO/IAEA International Symposium on Applications of Gene-based Technologies for Improving Animal Production and Health in Developing Countries (see http://www.iaea.org/programmes/nafa/d3/mtc/final-report-int-symposium.pdf).

C.5. Food Safety and Safety of Plant and Animal Products

80. Irradiation and other nuclear techniques are increasingly used by the private sector to ensure food safety and to minimize risks arising from chemical, biological and physical hazards and to facilitate domestic and international trade. This growing demand relates to integrated agricultural systems for the production, processing and hygienic control of plant and animal products and includes the management of environmental hazards. It is envisioned that governments will increasingly focus on the control of food safety hazards at their origin in the production of products of particular interest to their constituents, including fresh fruits and vegetables, meat and meat products and dairy commodities. It is also anticipated that in spite of the proven safety and wholesomeness of irradiated foods, negative consumer perceptions and acceptance of food irradiation will continue to hinder its application and therefore, training and education programmes and information related to the benefits of the technology are needed to promote its greater use by the food industry.

D. Human Health

D.1. Nutrition

81. The use of isotopic technology is increasingly recognized as more suitable and accurate than conventional methods for developing and evaluating nutrition programmes. Isotope tracers are recommended as cost-effective techniques for the evaluation of mineral and vitamin uptake and absorption from fortified foods. Isotope dilution techniques can be used to monitor changes in body composition in cases of obesity, protein and energy malnutrition or in patients suffering from HIV/AIDS or cancer. These techniques use either deuterium or oxygen-18.

82. Accurate information on energy requirements is also recognized as a valuable input for strategies on population healthcare management. The doubly labelled water method with both deuterium and oxygen-18 is now the accepted standard technique used for the measurement of energy expenditure, from which energy requirements of populations under different circumstances may be calculated.

83. Assessment of body composition, which is important for health or disease development, has also become more important. A promising technique for the measurement of body composition is the Dual Energy X-Ray Absorptiometry (DEXA) technique, which although first developed to measure bone mineral density, is now considered an accurate tool for determining gross and regional fat distribution.

D.2. Nuclear Medicine

84. Studies using short-lived radionuclides with nuclear medicine techniques help clinicians to examine metabolic processes in patients. The normal metabolism is always affected by disease, and changes usually occur prior to the appearance of anatomical alterations that are recognizable with classical X-ray imaging techniques. The early detection of metabolic changes thus has the potential to provide a better basis for medical or surgical intervention. Standardized protocols that are based on such studies and which have been developed for cardiac or cancers patients are increasingly used for optimizing clinical management, and ultimately the final treatment outcome. This has become possible with positron emission tomography (PET), which is one of the fastest growing nuclear medicine techniques. It is becoming a standard clinical application of nuclear medicine, and uses ultra short-lived radioisotopes attached to biological markers. In particular, with the use of radiolabelled glucose referred to as FDG (fluoro18deoxyglucose) or C11-choline, glucose and amino acid metabolism in organs can be studied. PET functional images are then fused with X-ray computed tomography images, providing details on health changes in individual patients, which can help improve cancer management. Unlike single photon emission computed tomography (SPECT), the most widely used in vivo imaging technique in nuclear medicine, PET will need time for implementation in developing countries because of present high costs.

85. There are numerous radioisotopic in vitro procedures for genotyping and molecular profiling applicable to clinical molecular biology. These procedures are becoming increasingly important in several clinical and pre-clinical conditions, from determining changes in cancer cells to drug resistance in malaria parasites and tuberculosis.

86. In addition to the well established treatment of thyrotoxicosis and thyroid cancer, the major development in the application of nuclear medicine therapeutics is the arrival of radiolabelled monoclonal antibodies and radiolabelled peptides to treat diseases such as lymphomas and neuro-endocrine tumours. This will result in targeted therapeutics that can be applied to selected types of cancers and with significantly fewer side effects compared with conventional chemotherapy. A variety of radiopharmaceuticals is also available for pain palliation in advanced cancer disease, leading to cost-effective improvement in quality of life of patients affected from bone metastases and freeing them from the need for daily opiate drug treatment and other costly pharmaceutical support.

D.3. Radiotherapy

87. 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 patients' survival in 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 targets in ways that will preserve their radio-sensitizing effect on the cancerous tissues, while decreasing the toxicity to the healthy tissues. The IAEA is promoting research into monitoring the delayed toxicity of chemical modifiers of the effects of radiation, as well as identifying molecular targets that help cancer cells escape death after irradiation, and targets that are responsible for radiation injury to healthy tissues.

88. For many years radiotherapy has been delivered five times per week as a standard practice. Some recent studies have shown that delivering this treatment more than five times per week (accelerated radiotherapy) can improve the tumour control in some kinds of cancers without significantly increasing the toxicity. The IAEA is promoting research activities in this field.

89. Advances in technology, such as intensity-modulated radiotherapy (IMRT), proton and heavy particle radiotherapy, and tomotherapy, which allows conformal treatment of a tumour and on-line

imaging during treatment, make it possible to increase the physical dose to the cancerous 'target volume' without increasing the dose to the healthy organs outside of this volume. Although currently expensive, the costs of these technologies can be reduced by taking advantage of the improved physical dose distribution by delivering the treatment in fewer sessions (hypo-fractionation) than during traditional radiotherapy.

D.4. Dosimetry and Medical Radiation Physics

90. Quality assurance in radiation medicine helps ensure its safe and effective application. The introduction of new, complex treatment techniques has resulted in increased demand for accurate dosimetry. Even as the complexity of the treatment increases, the basic need for accurate beam calibration remains crucial. The current worldwide trend in radiotherapy dosimetry is towards the implementation of dosimetry codes of practice based on calibration in terms of absorbed dose to water, such as the IAEA's international code of practice *Absorbed Dose Determination in External Beam Radiotherapy* (technical Reports Series No. 398). Although dosimetry in diagnostic radiology has not yet reached the same level of standardization as in radiotherapy, it continues to be important in ensuring patient safety. The IAEA and the International Commission on Radiation Units and Measurements are developing an international dosimetry code of practice in this area.

91. The use of patient data in individualized treatment planning for therapeutic nuclear medicine is growing in importance, particularly for paediatric patients. Accurate treatment planning requires a standardized approach to measure the necessary physical and biological parameters for the patient and to apply these data to appropriate models. The IAEA is working to develop codes of practice to address the imaging and radioactivity measurement components of the process.

92. One of the new challenges in medical radiation physics originates from the evolution of three-dimensional conformal radiotherapy towards image-guided radiotherapy (IGRT), which has the capability to track and maintain beam accuracy following changes in tumour position and patient anatomy. IGRT aims to improve the clinical outcome by delivering higher doses to the tumour with reduced treatment margins, thus sparing organs at risk and protecting normal tissue. IGRT takes into account changes in anatomy, organ motion, and changes in tumour size and position in the preparation of the treatment plan and monitors these changes during the course of the treatment. It takes advantage of recent developments in imaging for radiotherapy, such as MR-CT (magnetic resonance-computed tomography) image fusion or PET-CT image registration, as well as 4D CT and cone CT, which are now available in the modern treatment room. For the verification of the treatment delivery, multiple portal images are obtained using electronic portal imaging devices (EPIDs), which verify the patient position and map the delivered doses.

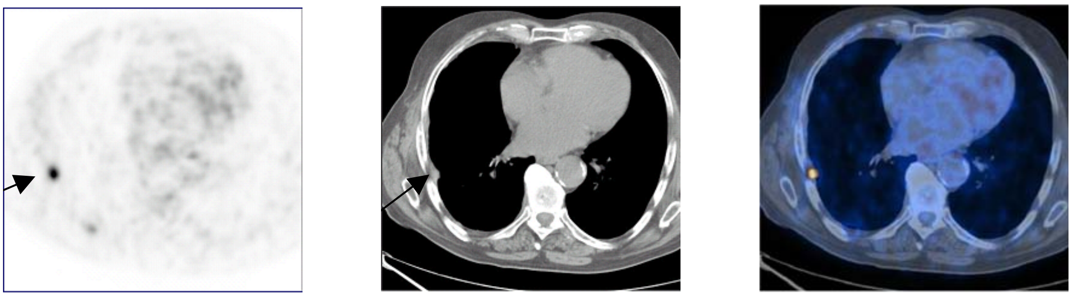

Figure D-1. Multimodality imaging (image fusion): Improved cancer diagnosis (staging) using multimodality imaging 'fusion' of PET (left) and CT (centre) images. The right-hand picture shows the combined (fused) image, which provides a precise anatomical location of the tumour deposit barely visible in the CT image alone. (Image courtesy of Dr. S. Fanti, Univ. of Bologna, Italy)

93. Audits in radiotherapy constitute an important means of assuring adequate quality of the process both for traditional and novel techniques. The current trend is to extend the audits dealing with physics aspects to comprehensive reviews involving multidisciplinary audit teams. At the same time new audit methods for radiotherapy dosimetry are being developed to keep pace with the recent progress in radiotherapy technology.

E. Water Resources

94. Water resource management continues to be high on the international agenda. The United Nations has proclaimed 2005–2015 as the “Decade of Water for Life”, recognizing the critical link between water and development. There is a rising trend to utilize groundwater to meet the growing demand for water, largely due to the finite availability of surface water. Isotopic techniques are increasingly used in efforts to manage groundwater sustainably, particularly for understanding certain aspects of the water cycle, such as the origin of the water, recharge rates, and water flows — information needed to make sound management decisions.

95. Given the increased reliance on groundwater to meet growing water resource needs, international organizations, including the IAEA, are developing a “World Groundwater Vision” to be presented at the 4th World Water Forum in Mexico in 2006. This vision is intended to serve as a blueprint for the effective management of groundwater, and will include guidelines on how to utilize appropriately science and technology, such as isotope hydrology, for effective groundwater management.

96. There is a growing focus on the management of transboundary aquifers. A recent global water inventory identified over 400 such ‘shared’ aquifers. The Global Environment Facility, the World Bank, the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), the IAEA and others, recognizing the potential for conflict over shared water resources, have begun supporting projects to facilitate effective joint management. Isotopic tools for identifying risks of pollution, defining the movement of water, age of water and determining pollution sources are emerging as essential tools for transboundary groundwater management and the development of approaches for sustainable groundwater resources management.

F. Marine and Terrestrial Environments

F.1. Marine Environment

F.1.1. Radiotracing contaminants in seafoods

97. Applications of radiotracing nuclear technologies to assess and monitor land-based contaminants in coastal fisheries are becoming increasingly important tools for both health and trade. Seafood toxicity management with respect to harmful algal blooms (HABs), which are a growing problem worldwide, is, for example, assisted by a nuclear-based receptor-binding assay (RBA) to more efficiently support the regulation of paralytic shellfish poisons derived from HABs. The likely future reduction in acceptable levels of particular toxins in shellfish will require the use of more sensitive assays such as the RBA.

98. Radiotracer techniques are also valuable to combat the problems of land-based metal contaminants in the coastal environments. Understanding the effects and exposure pathways of metals from mining activities on selected marine species can be achieved by using radiotracers such as nickel-63, cobalt-57, manganese-54, cadmium-109, zinc-65 and silver-110m. These radiotracers are also being assessed for their effectiveness as pollution monitors to assist fishing industries. Similarly, arsenic contaminants have been evaluated in the radioecology experimental facility at the Marine Environmental Laboratory in Monaco for their capacity to accumulate in local fisheries using the radiotracer arsenic-73. Future trends include the application of nuclear imaging technologies to marine organisms, and the use of experimental and field-based data on contaminants for risk-based assessments of their likely impact on fisheries and consumers.

F.1.2. Isotopic tracing of the El Niño Southern Oscillation (ENSO) phenomenon

99. ENSO’s impact on both the marine environment and the Earth’s climate has been regarded as a most important environmental phenomenon affecting the climate of the Pacific region, as well as the whole Earth, with important consequences for fish populations and rainfall, including the formation of cyclones. New isotopic studies of the ENSO phenomenon showed that during an El Niño event sea-surface temperature increases and is accompanied by larger evaporation losses and isotopic fractionation, resulting in changes of hydrogen-2, carbon-13, carbon-14 and oxygen-18 isotopic compositions of seawater. It has been recognized that corals archive isotopic records in their annual growth bands and therefore may be used for the reconstruction of past ocean temperature records, after the establishment of an absolute chronology of their growth, which could be accomplished by independent radionuclide dating of coral bands using thorium/uranium dating methods.

100. Using dated corals, isotope oceanographers and climatologists are now developing chronologies for corals and sediments going back several hundreds of years. When completed, this will enable sea-surface temperature and the frequency and intensity of past El Niño events to be reconstructed for different locations, in order to better predict ocean–atmosphere coupling in the future.

F.1.3. Disequilibria in natural radionuclides track carbon sinks in the ocean interior

101. Up to 50% of fossil fuel-derived CO_2 in the atmosphere is drawn down into the interior of the ocean by physico-chemical dissolution of the CO_2 gas and by biological uptake and sedimentation of dead organic matter. Tracking this vertical carbon flux of particles to the seabed has challenged marine scientists for many years until the recent discovery that thorium-234 (produced by natural uranium-238 in seawater) is scavenged onto the surface of sedimenting particles. Its half-life of 24 days serves as an excellent ‘clock’ to track the age and fate of sedimenting particles in the ocean. Using the thorium-234 technique, oceanographers have discovered a hundred-fold variation in ocean

carbon sinks in different seas, which is strongly related to the growth and abundance of microscopic plants or phytoplankton. This ‘biological’ ocean pump of carbon is now recognized as crucial in regulating the limit to which the ocean will continue to absorb CO_2 and other greenhouse gases accumulating in the atmosphere.

F.2. Terrestrial Environment

F.2.1. Radioecological studies

102. Radioecological studies were originally developed primarily from investigations of the effects of nuclear weapons testing, and releases from reactors and reprocessing operations or accidents. Recent years have seen increased interest from Member States in a variety of other sources of radiological impact, such as depleted uranium remains from military operations; mining and milling operations and naturally occurring radioactive materials (NORMs). In addition, the use of nuclear techniques and the application of derived models and parameters in eco-toxicological assessment studies for other pollutants than radionuclides, as well as the evaluation of synergistic effects of mixed pollution are receiving more attention globally.

103. In all these cases, managers and regulators require information on which they can base decisions. Provision of basic data is important but insufficient for their needs. An additional tool is the use of predictive models, and the IAEA has been active over a long period in the development of both generic and specific models, and in the evaluation and tabulation of model parameter values.

104. Recent developments in remote sensing tools, in particular improved spatial and spectral resolutions, are providing new opportunities. An example is airborne gamma ray surveys. Traditionally these were used for mining exploration but recent improvements in spatial resolution have resulted in their use in environmental and other resource management applications. Geographic information systems (GISs) also provide a mechanism of storing, processing and displaying geographic data of various types in a way that is useful for end users.

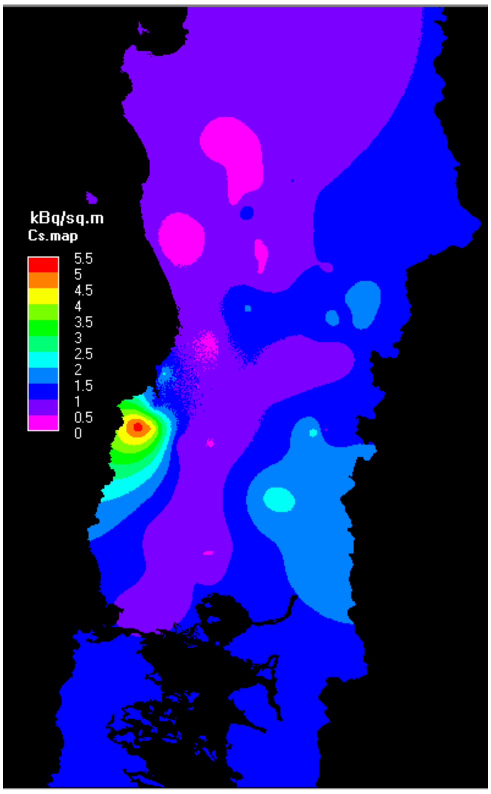

Figure F-1. Example of the use of GIS in support of an environmental decision support system: ^{137}Cs deposition map for Chile. Produced using contouring techniques together with data for rainfall and ^{137}Cs ground measurements[11].

G. Research Reactor Utilization

105. Research reactors continue to engage interest in terms of their need for sustained utilization and issues of safety and security. The Scientific Forum at the 2004 session of the General Conference concluded that "while research reactors will continue to play a crucial role in nuclear science and technology, it is important to ensure operational ability in terms of technical and financial resources, meeting the current standards of nuclear and conventional safety, and other aspects related to physical security, public acceptance and environmental responsibility. The technical aspects that need to be addressed include the capability for safe spent fuel management and storage, reactor refurbishment when required and the eventual decontamination and decommissioning of the facility".

106. The replacement of high enriched uranium targets by low enriched uranium targets for large-scale production of molybdenum-99 is under review to identify areas requiring support and international cooperation.

107. A variety of other radioisotopes (more than 150 in different forms) continue to be in extensive use in medicine and industry. Radionuclides suitable for therapeutic applications and easily producible

[11] (Ref) SCHULLER, P., VOIGT, G. (Eds), Development of an Environmental Decision Support System (EDSS) to Identify Radioecological Sensitive Areas for Radiocaesium in Chile (CHIRSA), Final Report to Volkswagen Foundation, Neuherberg (2004).

in research reactors, such as ^{177}Lu, are being intensively evaluated for development of radiopharmaceuticals.

108. Neutron beams from research reactors provide a powerful probe for a variety of applications that make use of neutron scattering and radiography techniques. The special advantage of neutrons is their sensitivity to light elements (unlike X-rays which are sensitive to heavier elements). Consequently, superior resolution is achieved by neutron radiography of industrially important test materials, including for example the investigation of fuel elements. Advances in material characterization and material science using neutron scattering aid in the development of novel materials. While such techniques are already in use in some countries, the growing awareness of potential new applications and wider adaptation of these techniques has led to increasing attention being focused on them.

H. Accelerator Utilization

109. The development of robust accelerators over the past decade has enabled many laboratories to modernize their facilities with low maintenance, highly reliable systems for safe operation with non-specialist operators. The utilization of smaller and more compact accelerators for applied science and technology rather than for basic science is increasing. Recent technical developments have now made possible the operation of small accelerators outside of research laboratories for in-situ applications.

110. New accelerator-based spallation neutron sources presently under construction in Japan and the USA will become the premier facilities for exploiting neutrons in science and technology. These facilities are examples of accelerator driven neutron sources based on high-energy particle accelerators operating at energies over 1 GeV. Their advantages over conventional reactor sources are derived partly through the use of pulsed operation, which is more efficient, and a mode not available from reactor-based sources. Furthermore, their pulsed operation can be combined with suitable instrumentation to use neutrons with up to three orders of magnitude more efficiency.

111. The scope for applying accelerator-based nuclear techniques to support material science studies, development of novel materials as well as environmental studies is promising. There is also considerable interest in the use of ion beam analysis and accelerator mass spectrometry, for example, for carbon-14 dating, drug research and environmental monitoring.

I. Industrial Process Monitoring

112. Computed tomography imaging technology is used for diagnosing industrial multiphase process units. Multiphase reactor technology is the basis of petroleum refining, synthesis gas conversion to fuels and chemicals, bulk commodity chemicals production, manufacture of special chemicals and polymers, and conversion of undesired products into recyclable materials. In process engineering, both gamma transmission and gamma emission tomography are used for the inspection of packed columns, bubble columns, multiphase flows, fluidized beds and porous media. The technology is still evolving, but it has the potential for enabling great improvements in efficiency and safety in multiphase process industries. Adapting the developments in medical imaging, the SPECT method is being introduced on a laboratory scale for industrial processes. Two-dimensional imaging with a gamma camera is also an

attractive technique under development. Single particle tracking techniques, in particular to investigate fluidized bed reactors, has been progressing.

I.1. Radiation Processing — Nanotechnology

113. Nanotechnology is one of the fastest growing areas in science and engineering, and of considerable economic value. The ability to fabricate precision structures with nanometric dimensions and precision is of fundamental importance to the full utilization of the technology. Radiation is an effective tool in this regard, for example for surface modification and curing. New trends for precision treatment have emerged, for example, for ion track membranes and controlled release drug-delivery systems. Radiation-based technologies using X-rays, electron beams and ion beams are the key to a variety of approaches to nanopatterning (the creation of nano-sized pores), while electron beam aided lithography is gaining increased attention. Radiation synthesis of metallic nanoparticles (e.g. copper, silver) in polymers and zeolites is being studied for application in photoluminescent, photoelectric, and solar cells. The solution of metal salts is exposed to gamma rays and the reactive species generated by the radiation reduce the metal ion to the zero-valent state. Metal sulphide semiconductors of nanometric sizes are prepared using gamma irradiation of a suitable solution of monomer, sulphur and metal sources.