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Nuclear Technology Review 2010

Report by the Director General

Summary

- In response to requests by Member States, the Secretariat produces a comprehensive Nuclear Technology Review each year. Attached is this year's report, which highlights notable developments principally in 2009.
- The *Nuclear Technology Review 2010* covers the following areas: power applications, advanced fission and fusion, atomic and nuclear data, accelerator and research reactor applications, nuclear technologies in food and agriculture, human health, environment, water resources, and radioisotope production and radiation technology. Additional documentation associated with the *Nuclear Technology Review 2010* is available on the Agency's website[1] in English on developments in nuclear medicine for cancer management, nuclear techniques to address transboundary animal diseases, nuclear techniques for marine pollution monitoring, decommissioning of nuclear facilities, human resources for nuclear power expansion, infrastructure for new nuclear power programmes, and the production and supply of molybdenum-99.
- Information on the IAEA's activities related to nuclear science and technology can also be found in the IAEA's Annual Report 2009 (GC(54)/4), in particular the Technology section, and the Technical Cooperation Report for 2009 (GC(54)/INF/4).
- The document has been modified to take account, to the extent possible, of specific comments by the Board of Governors and other comments received from Member States.

[1] http://www.iaea.org/About/Policy/GC/GC54/Agenda/index.html

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Nuclear Technology Review 2010

Report by the Director General

Executive Summary

1. In 2009, construction started on twelve new nuclear power reactors, the largest number since 1985, and projections of future nuclear power growth were once again revised upwards. However, only two new reactors were connected to the grid, and, with three reactors retired during the year, the total nuclear power capacity around the world dropped slightly for the second year in a row.

2. Current expansion, as well as near term and long term growth prospects, remain centred in Asia. Ten of the twelve construction starts were in Asia, as were both of the new grid connections. Although the global financial crisis that started in the second half of 2008 did not dampen overall projections for nuclear power, it was cited as a contributing factor in near-term delays or postponements affecting nuclear projects in some regions of the world.

3. In some European countries where previously there were restrictions on the future use of nuclear power, there was a trend towards reconsidering these policies.

4. Interest in starting new nuclear power programmes remained high. Over 60 Member States have expressed to the Agency interest in considering the introduction of nuclear power, and, in 2009, the Agency conducted its first Integrated Nuclear Infrastructure Review Missions in Jordan, Indonesia and Vietnam.

5. Estimates of identified conventional uranium resources (at less than $130/kg U) increased slightly, due mainly to increases reported by Australia, Canada and Namibia. Uranium spot prices declined, and final data for 2009 are expected to show a consequent decrease in uranium exploration and development.

6. The Board of Governors has authorized the Agency's Director General to sign an agreement with the Russian Federation to establish an international reserve of low enriched uranium (LEU). It would contain 120 tonnes of LEU that could be made available to a country affected by a non-commercial interruption of its LEU supply. The agreement between the Agency and the Russian Federation was signed in March 2010.

7. The Swedish Nuclear Fuel and Waste Management Company (SKB) selected Östhammar as the site for a final spent fuel geological repository, following a nearly 20-year selection process. In the USA, the Government decided to terminate its development of a permanent repository for high level waste at Yucca Mountain, while continuing the licensing process. It plans to establish a commission to evaluate alternatives.

8. With respect to nuclear fusion, site preparations for the International Thermonuclear Experimental Reactor (ITER) were completed and procurement arrangements signed for facilities worth approximately €1.5 billion, about a third of total anticipated procurements. Construction of the National Ignition Facility in the USA was completed.

9. Food security, human health including disease prevention and control, environmental protection, water resource management as well as the use of radioisotopes and radiation are all areas where nuclear and isotopic techniques are beneficial in supporting socio-economic development in many countries throughout the world.

10. In the food and agriculture area, nuclear techniques are being used, together with complementary techniques, to address a growing number of insect pests that threaten agricultural productivity as well as international trade. The analysis of the genetic resources of livestock is a high international priority because it provides crucial options for the sustainable expansion of livestock production. Nuclear techniques can assist in these efforts. As concern over carbon emissions grows, the option of storing (sequestering) carbon in soils is of increasing interest. Isotopic tools are useful for determining the sequestration capacity of specific land areas.

11. Diagnostic imaging continues to be one of the most innovative areas of modern medicine. Nuclear techniques such as positron emission tomography (PET), single photon emission computed tomography (SPECT) and computed tomography (CT) are increasingly being merged into hybrid-imaging systems such as SPECT/CT and PET/CT. These hybrid imaging systems allow for a combined investigation of both the anatomy and the function of human organs. This hybrid imaging is of growing importance in the areas of cardiology and cancer. The recent results of the application of stable isotope techniques to assess bioavailability of iron and provitamin A carotenoids in vulnerable population groups will assist policy makers, health professionals and other stakeholders, in determining next steps and response options.

12. In the natural resource management field, nuclear techniques are being used to assess the amount of freshwater that is entering coastal areas via coastal aquifers. This is important because such submarine groundwater discharge (SGD) can be important sources of freshwater as well as can, in some cases, be a source of pollutants to coastal areas. Increasingly, stable isotopes are used to understand the spatial distribution of various processes that affect groundwater availability and quality both at the local as well as at regional levels. Such information can provide a key baseline for assessing the impact of climate change and other factors on groundwater resources.

13. The ever increasing demand for radioisotopes for medical and industrial applications as well as advances in related technologies received worldwide attention in 2009 owing to the high level of media coverage of the serious shortages faced in the supplies of medical isotopes, especially fission-produced molybdenum-99. New radiation technology applications continue to be developed as evidenced by the recent use of a new electron beam methodology that offers a chemical-free alternative for sterilizing or sanitizing aseptic packaging materials and containers.

A. Power Applications

A.1. Nuclear power today

14. For nuclear power, 2009 was the second year in a row with a high number of construction starts on new reactors and with upward revisions in projections of future nuclear power growth. While 2008 was distinctive as the first year since 1955 in which no new reactors were connected to the grid, 2009 saw two new grid connections, Tomari-3 (866 MW(e)) in Japan and Rajasthan-5 (202 MW(e)) in India).

15. As of 1 January 2010, there were 437 nuclear power reactors in operation worldwide, with a total capacity of 371 GW(e) (see Table A-1). This was about 1.5 GW(e) less than at the end of 2008 due partly to three retirements, Hamaoka-1 and -2 in Japan and Ignalina-2 in Lithuania, which was retired at the end of the year.

16. There were twelve construction starts: Hongyanhe-3 and -4, Sanmen-1 and -2, Yangjiang-2, Fuqing-2, Fangjiashan-2, Haiyang-1 and Taishan-1 (all 1000 MW(e)) in China; Shin-Kori-4 (1340 MW(e)) in the Republic of Korea; and Novovoronezh 2-2 (1085 MW(e)) and Rostov-3 (1011 MW(e)) in the Russian Federation. Active construction resumed on Mochovce-3 and -4 (both 405 MW(e)) in Slovakia. This compares with ten construction starts in 2008 and, in 2007, eight construction starts plus the resumption of active construction at one reactor.

17. A total of 56 reactors were therefore under construction at the end of the year, the largest number since 1992.

18. Current expansion, as well as near term and long term growth prospects, remain centred in Asia. Of the twelve construction starts in 2009, ten were in Asia. As shown in Table A-1, 36 of the 56 reactors under construction are in Asia, as were 30 of the last 41 new reactors to have been connected to the grid. China's target is 40 GW(e) of nuclear power capacity in 2020, compared to 8.4 GW(e) today. Indian Prime Minister Manmohan Singh, in opening the International Conference on Peaceful Uses of Atomic Energy in New Delhi in September, said India could potentially install 470 GW(e) by 2050.

19. In Finland, applications were submitted to the Government for 'decisions in principle' on the construction of two new nuclear reactors. However, construction of Olkiluoto-3 was behind schedule.

20. The recent trends of uprates and renewed or extended licences for many operating reactors continued in 2009. In the USA, the Nuclear Regulatory Commission (NRC) approved eight more licence renewals of 20 years (for a total licensed life of 60 years) bringing the total number of approved licence renewals to 59. The UK Nuclear Installations Inspectorate approved renewed periodic safety reviews for two reactors, allowing an additional ten years of operation. Spain's Garona nuclear power plant was granted a four-year licence extension, and operating licences for Canada's Bruce A and Bruce B nuclear power plants were renewed for an additional five years.

21. In some European countries where previously there were restrictions on the future use of nuclear power, there was a trend towards reconsidering these policies.

22. Although the global financial crisis that started in the second half of 2008 did not dampen overall projections for nuclear power (see Section A.2), it was cited as a contributing factor in near-term delays or postponements affecting nuclear projects in some regions of the world. Vattenfall announced

in June that it was putting decisions on nuclear new build in the UK on hold for 12–18 months, citing the economic recession and market situation. Financing difficulties were cited in connection with the withdrawal of the utilities GDF SUEZ and RWE from the Belene project in Bulgaria. The Russian Federation announced that for the next several years, because of the financial crisis and lower projected electricity use, it would slow planned expansion from two reactors per year to one. Ontario, Canada, suspended procurement activities for two new nuclear power reactors to be built at its Darlington site because of reduced electricity demand. In the USA, Exelon deferred major pre-construction work on a proposed new nuclear power plant in Texas, citing uncertainties in the domestic economy. Reviews of 5 of the 28 reactors in 18 combined licence applications in the USA had been suspended by the end of 2009 at the request of the applicants. In South Africa, Eskom extended the schedule for its planned next reactor by two years to 2018.

23. As with projections for future growth (Section A.2), however, interest in starting new nuclear power programmes remains high. Over 60 Member States have expressed to the Agency interest in considering the introduction of nuclear power. The number of Agency technical cooperation projects on the introduction of nuclear power tripled in 2009. A brochure on a new Agency service, *INIR Integrated Nuclear Infrastructure Review Missions: Guidance on Preparing and Conducting INIR Missions*, was issued, and the first INIR missions were conducted in Jordan, Indonesia and Vietnam. INIR missions are Agency-coordinated peer reviews conducted by teams of international experts on the basis of an *Evaluation of the Status of National Nuclear Infrastructure Development*, published by the Agency in late 2008. The objective and scope of each of these reviews are tailor-made to the needs of the requesting Member State. As with a self-assessment, the INIR mission is intended to help a country identify gaps between the milestones and the current level of development of its programme and effectively address these gaps.

Table A-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 1 January 2010)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2009		Total Operating Experience through 2009	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	7.6	7.0	62	7
ARMENIA	1	375			2.3	45.0	35	8
BELGIUM	7	5 902			45.0	51.7	233	7
BRAZIL	2	1 884			12.2	2.9	37	3
BULGARIA	2	1 906	2	1 906	14.2	35.9	147	3
CANADA	18	12 569			85.3	14.8	582	2
CHINA	11	8 438	20	19 920	65.7	1.9	99	3
CZECH REPUBLIC	6	3 678			25.7	33.8	110	10
FINLAND	4	2 696	1	1 600	22.6	32.9	123	4
FRANCE	59	63 260	1	1 600	391.8	75.2	1 700	2
GERMANY	17	20 480			127.7	26.1	751	5
HUNGARY	4	1 889			14.3	43.0	98	2
INDIA	18	3 987	5	2 708	14.8	2.2	318	5
IRAN, ISLAMIC REPUBLIC OF			1	915				
JAPAN	54	46 823	1	1 325	263.1	29.2	1 440	8
KOREA, REPUBLIC OF	20	17 705	6	6 520	141.1	34.8	339	7
MEXICO	2	1 300			10.1	4.8	35	11
NETHERLANDS	1	487			4.0	3.7	65	0
PAKISTAN	2	425	1	300	2.6	2.7	47	10
ROMANIA	2	1 300			10.8	20.6	15	11
RUSSIAN FEDERATION	31	21 743	10	8 007	152.8	17.8	994	7
SLOVAKIA	4	1 762	2	782	13.1	53.5	132	7
SLOVENIA	1	666			5.5	37.8	28	3
SOUTH AFRICA	2	1 800			11.6	4.8	50	3
SPAIN	8	7 450			50.6	17.5	269	6
SWEDEN	10	9 036			50.0	37.4	372	6
SWITZERLAND	5	3 238			26.3	39.5	173	10
UKRAINE	15	13 107	2	1900	78.0	48.6	368	6
UNITED KINGDOM	19	10 137			62.9	17.9	1 457	8
UNITED STATES OF AMERICA	104	100 747	1	1 165	796.9	20.2	3 499	11
Total[b, c]	437	370 705	56	51 940	2 558.3	14%	13 913	0

a. Data are from the Agency's Power Reactor Information System (http://www.iaea.org/pris)

b. Note: The total includes the following data from Lithuania and Taiwan, China:

Lithuania: 10.0 TW·h of nuclear electricity generation, representing 76.2% of the total electricity generated;

Taiwan, China: 6 units, 4980 MW(e) in operation; 2 units, 2600 MW(e) under construction; 39.9 TW·h of nuclear electricity generation, representing 20.7% of the total electricity generated.

c. The total operating experience also includes shutdown plants in Italy (81 years), Kazakhstan (25 years, 10 months) and Lithuania (43 years, 6 months), Taiwan, China (170 years, 1 month).

A.2. Projected growth for nuclear power

24. Each year the Agency updates its low and high projections for global growth in nuclear power. In 2009, despite the financial crisis that started in late 2008, both the low and high projections were revised upwards. In the updated low projection, global nuclear power capacity reaches 511 GW(e) in 2030, compared to a capacity of 370 GW(e) at the end of 2009. In the updated high projection it reaches 807 GW(e). These revised projections for 2030 are 8% higher than the projections made in 2008.

25. The upward shift in the projections is greatest for the Far East, a region that includes China, Japan and the Republic of Korea. Modest downward shifts in the projections were made for North America and for Southeast Asia and the Pacific.

26. The financial crisis that started in late 2008 affected the prospects of some nuclear power projects, but its impact was different in different parts of the world. The regional pattern of revisions in the projections reflects, in part, the varying impacts of the financial crisis in different regions. The general upward revision in both the low and high projections reflects the judgement of the experts assembled by the Agency that the medium and long term factors driving rising expectations for nuclear power had not changed substantially. The performance and safety of nuclear power plants continued to be good. Concerns persisted about global warming, energy supply security, and high and volatile fossil fuel prices. All studies still projected persistent energy demand growth in the medium and long term.

27. What had changed since the projections made in 2008 was that the commitments of governments, utilities and vendors to their announced plans, and the investments they were already making in those plans, were generally perceived as becoming firmer over time. That raised confidence. Another change was that the lifting of nuclear suppliers' past restrictions on nuclear trade will allow India to accelerate its planned expansion of nuclear power.

28. The Agency's were not the only nuclear projections to have been revised in 2009. Updated projections were also published in 2009 by the US Energy Information Administration (EIA), the OECD International Energy Agency (IEA) and the World Nuclear Association (WNA). The EIA's range of projections became slightly narrower, the WNA's range became slightly broader, and the IEA's range was shifted very slightly upwards (both the low and high values increased). Figure A-1 compares the ranges of the 2009 nuclear projections of the EIA, IEA, IAEA and WNA.

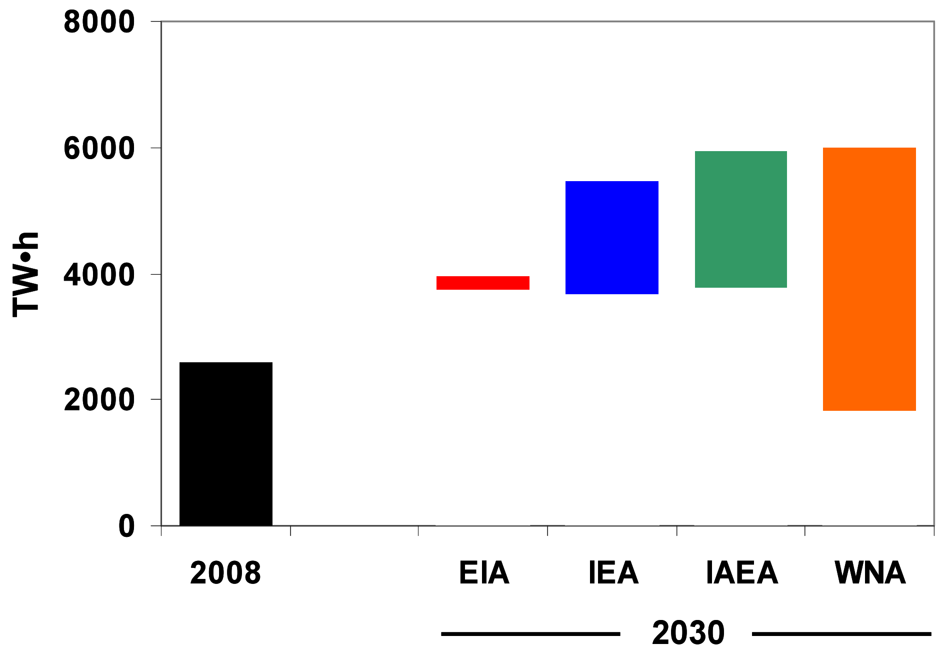

FIG. A-1. Comparison of nuclear power projections by the EIA, IEA, IAEA and WNA.

A.3. Fuel cycle[2]

A.3.1. Uranium resources and production[3]

29. Identified conventional uranium resources, recoverable at a cost of less than $130/kg U, are currently estimated at 5.7 million tonnes uranium (Mt U). This is an increase of over 0.2 Mt U, relative to 2007, due mainly to increases reported by Australia, Canada and Namibia. There are an additional 0.7 Mt U of identified conventional resources recoverable at costs between $130/kg U and $260/kg U. For reference, the spot price for uranium in 2009 fluctuated between $110/kg U and $135/kg U with a very gradual downward trend.

30. Undiscovered conventional resources are estimated at 6.3 Mt U at a cost of less than $130/kg U, with an additional 0.2 Mt U at costs between $130/kg U and $260/kg U. 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 3.6 Mt U of speculative resources for which production costs have not been specified.

31. Unconventional uranium resources and thorium further expand the resource base. Unconventional resources include uranium in seawater and resources from which uranium is only recoverable as a minor by-product. Very few countries currently report unconventional resources. Past estimates of potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonatite, black schist and lignite are of the order of 10 Mt U. Significant past production from phosphoric acid took place in Belgium, Kazakhstan and USA, and with higher uranium prices recently there is renewed interest in this area in Australia, Brazil, France, India, Jordan, Morocco, Tunisia and USA.

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[2] More detailed information on IAEA activities concerning the fuel cycle is available in relevant sections of the latest IAEA Annual Report (http://www.iaea.org/Publications/Reports/Anrep2009/index.html) and at http://www.iaea.org/OurWork/ST/NE/NEFW/index.html.

[3] This section is based on the forthcoming 'Red Book' (OECD/NEA–IAEA, *Uranium 2009: Resources, Production and Demand*, OECD, Paris (2010)).

Uranium extraction from coal ash piles from thermal power production is being studied in China. Thorium, which can also be used as a nuclear fuel resource, is abundant, widely distributed in nature, and an easily exploitable resource in many countries. Worldwide resources have been estimated to be about 6 Mt thorium. Although thorium has been used as fuel on a demonstration basis, significant further work is needed before it can be considered on an equal basis with uranium.

32. Seawater contains an estimated 4500 Mt U, but at a very low concentration of 3.3 parts per billion (ppb). Thus, 330 000 t of water would have to be processed to produce one kg of uranium. Currently, such production is too expensive. Research was carried out in Germany, Italy, Japan, UK and USA in the 1970s and 1980s. Current bench scale marine experiments in Japan indicate that uranium might possibly be extracted with braid type adsorbents moored to the sea floor, with a production capacity of 1200 t U per year at an estimated cost of about $300/kg U. Laboratory scale research is also being carried out in France and India.

33. Due to the drop in uranium spot prices relative to 2008, it is expected that when final data are available for 2009 they will show a decrease in uranium exploration and development. This is expected both for countries that have explored and developed uranium deposits in the past and for countries new to uranium exploration.

34. In 2008, uranium production worldwide was over 43 800 t U, up 6% from 41 300 t U in 2007. It is estimated that production will increase in 2009 to 49 000 t U. As shown in Figure A-2, Canada, Kazakhstan and Australia accounted for almost 60% of world production in 2008. These three together with Namibia, Niger, the Russian Federation, Uzbekistan and USA accounted for 93% of production.

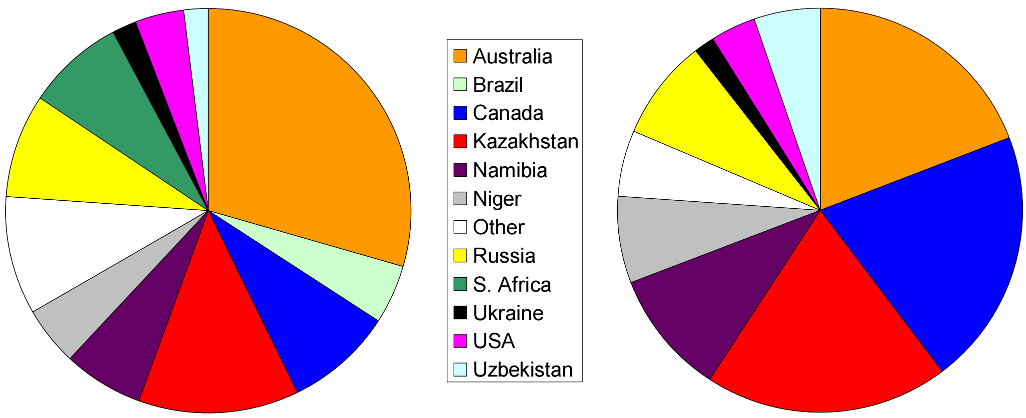

FIG. A-2. Geographical distribution of identified conventional uranium resources recoverable at less than $130/kg U (left) and of uranium production in 2008 (right).

35. Projected uranium production in 2009 was expected to cover only about 75% of the world's estimated reactor requirements of 65 400 t U. The remainder was covered by five secondary sources: stockpiles of natural uranium, stockpiles of enriched uranium, reprocessed uranium from spent fuel, mixed oxide (MOX) fuel with uranium-235 partially replaced by plutonium-239 from reprocessed spent fuel, and re-enrichment of depleted uranium tails (depleted uranium contains less than 0.7% uranium-235). At the estimated 2009 rate of consumption, the projected lifetime of the 5.7 Mt U of identified conventional resources recoverable at less than $130/kg U is almost 90 years. This compares favourably to reserves of 30–50 years for other commodities (e.g. copper, zinc, oil and natural gas).

A.3.2. Conversion, enrichment and fuel fabrication

36. Total global conversion capacity is about 76 000 tonnes of natural uranium per year for uranium hexafluoride (UF_6) and 4500 t U per year for uranium dioxide (UO_2). Current demand for UF_6 conversion is about 62 000 t U per year. In 2009, AREVA started construction on its new COMURHEX II conversion facilities to replace the older facilities at Malvési and Pierrelatte, France. COMURHEX II's design capacities for uranium tetrafluoride (UF_4) and UF_6 conversion are 15 000 t U each per year by 2012. In 2008, Cameco Corporation and Kazatomprom announced the establishment of a joint venture to develop a 12 000 tonne UF_6 conversion facility in Kazakhstan.

37. Total global enrichment capacity is currently about 60 million separative work units (SWUs) per year compared to a total demand of approximately 45 million SWUs per year. Three new commercial scale enrichment facilities are under construction, Georges Besse II in France and, in the USA, the American Centrifuge Plant (ACP) and the National Enrichment Facility (NEF). All use centrifuge enrichment. Georges Besse II and ACP are intended to allow the retirement of existing gas diffusion enrichment plants. At Georges Besse II rotation of the first centrifuge cascade took place in December 2009. At NEF the first centrifuge was installed in September 2009. For the ACP, there is still some doubt about the readiness of the technology.[4] The US NRC began formal reviews for two additional facilities, AREVA's proposed Eagle Rock Enrichment Facility in Idaho and Global Laser Enrichment's proposed laser enrichment facility in North Carolina.

38. Japan Nuclear Fuel Limited (JNFL) expects to begin commercial operation of improved centrifuge cascades at Rokkasho-mura around 2011 and to expand capacity from 150 000 SWUs today to 1.5 million SWUs by 2020. Current enrichment capacity in China, using Russian centrifuges, is 1.3 million SWUs, and Russia and China recently agreed to add 0.5 million SWUs. Limited enrichment facilities for domestic needs exist in Argentina, Brazil, India and Pakistan. Ukraine joined Armenia, Kazakhstan and the Russian Federation as members of the International Uranium Enrichment Centre (IUEC). The IUEC was established in 2007 in Angarsk, Russian Federation.

39. In November the Board of Governors authorized the Agency's Director General to sign an agreement with the Russian Federation to establish an international reserve of low enriched uranium (LEU). It would contain 120 tonnes of LEU that could be made available to a country suffering a non-commercial interruption of its LEU supply. The Director General would have the sole authority to release LEU from the reserve, in accordance with criteria in the agreement with the Russian Federation. The Russian Federation would be obligated to issue all authorizations and licences needed to export the LEU, and the country receiving the LEU would pay the market price prevailing at the time. The agreement between the Agency and the Russian Federation was signed in March 2010.

40. Total global fuel fabrication capacity is currently about 13 000 tonnes of uranium (t U) per year (enriched uranium) for light water reactor (LWR) fuel and about 4000 t U per year (natural uranium) for pressurized heavy water reactor (PHWR) fuel. Total demand is about 10 400 t U per year. Some expansion of current facilities is under way, for example in China, Republic of Korea and USA. The current fabrication capacity for MOX fuel is around 250 tonnes of heavy metal (t HM), mainly located in France, India and UK with some smaller facilities in Japan and Russian Federation. Additional MOX fuel fabrication capacity is under construction in the USA (to use surplus weapon-grade plutonium). Genkai-3 in Japan started operating with MOX fuel in November, making it the first Japanese reactor to use MOX fuel. Worldwide, 31 thermal reactors currently use MOX fuel.

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[4] The US Department of Energy postponed its review of a requested loan guarantee to allow issues relating to the readiness of ACP's enrichment technology to be addressed.

A.3.3. Back end of the fuel cycle

41. The total amount of spent fuel that has been discharged globally is approximately 320 000 tonnes of heavy metal (t HM). Of this amount, about 95 000 t HM have already been reprocessed, and about 225 000 t HM are stored in spent fuel storage pools at reactors or in away-from-reactor (AFR) storage facilities. AFR storage facilities are being regularly expanded both by adding modules to existing dry storage facilities and by building new facilities. Total global reprocessing capacity is about 5000 t HM per year. Completion of the new Rokkasho reprocessing plant in Japan was postponed until 2010.

42. The Swedish Nuclear Fuel and Waste Management Company (SKB) selected Östhammar as the site for a final spent fuel geological repository, following a nearly 20-year process that narrowed the list of applicant sites to two in 2002. Subsequent site investigations concluded that the bedrock in Östhammar was more stable with less water than that in Oskarshamn, the other potential site. SKB plans to apply for a construction licence in 2010 with operation targeted for 2023.

43. Site investigations for repositories at Olkiluoto in Finland and in the Bure region in France continued on schedule with operation targeted for 2020 and 2025 respectively.

44. In the USA, the Government decided to terminate its development of a permanent repository for high level waste at Yucca Mountain, while continuing the licensing process. It plans to establish a commission to evaluate alternatives.

45. In the UK a voluntary siting process has been initiated. Two boroughs in the neighbourhood of Sellafield have expressed an interest.

46. In 2009, completion of the decommissioning of the Rancho Seco nuclear power reactor in California, USA, brought the number of power reactors worldwide that had been fully dismantled to 15. Fifty-one shutdown reactors were in the process of being dismantled, 48 were being kept in a safe enclosure mode, 3 were entombed, and, for 6 more, decommissioning strategies had not yet been specified.

A.4. Additional factors affecting the growth of nuclear power

A.4.1. Economics

47. The *Nuclear Technology Review 2009* reported that the range of cost estimates for new nuclear power plants had grown at its upper end compared to the range of $1200–2500 per kW(e) that had been reported in the *Nuclear Technology Review 2006*. In the past year, cost estimates remained high. Figure A-3 shows recent overnight cost estimates collected by the Agency, grouped by region.[5]

48. The overall pattern in the figure is consistent with the observation that experience reduces cost uncertainty. Although there are several reasons for low costs in Asia (i.e. input costs that are generally lower than elsewhere and cost quotations that sometimes include only imported components), it is also the region with the most recent experience in building new reactors.

[5] The data are taken from publicly available cost studies and industry quotations. All the caveats that were cited in the *Nuclear Technology Review 2009* apply: differences in cost estimates may reflect different definitions of overnight costs, whether the estimate is for a greenfield site or a site with existing reactors, whether the site is in a seismically active area, variations in labour and material costs, different localization requirements, different percentages of plant components manufactured or procured locally, different subsidies and financial guarantees, differences in regulatory requirements and their predictability, different contractual arrangements, different exchange rates and expectations about inflation, and different technologies.

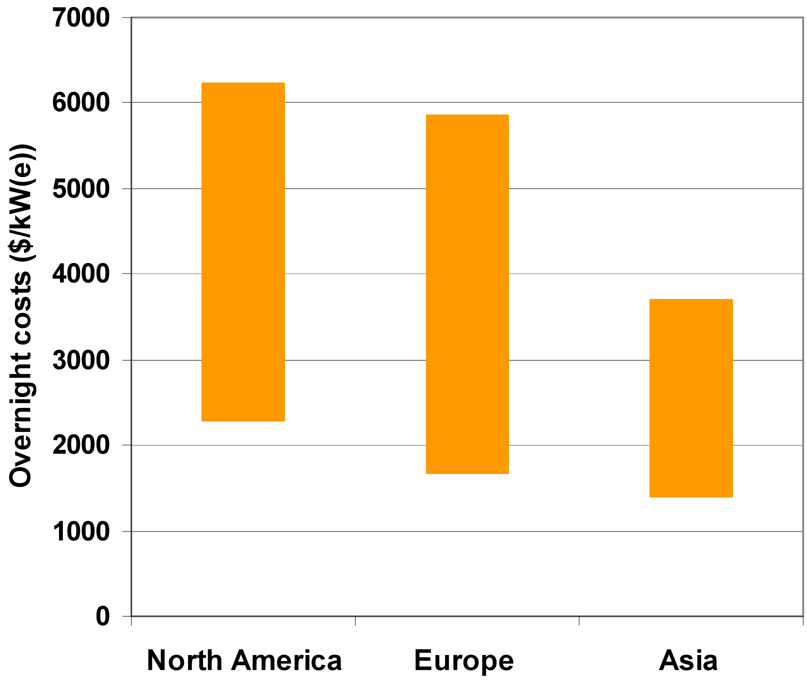

FIG. A-3. Ranges for overnight cost estimates by region, from 2007–2009 (2008 dollars).[6]

49. As more cost estimates for specific nuclear power projects have been reported, like those collected in Figure A-3, fewer academic estimates of nuclear power costs have been published. A few such studies, however, were published in 2009.

50. The Massachusetts Institute of Technology (MIT) updated a cost study for the USA that it had done in 2003[7] — its updated overnight cost estimate of $4000/kW(e) is very close to the mean of the estimates for North America in Figure A-3. The updated MIT study concludes that, in the USA, the cost of capital will be higher for nuclear power than for coal- and natural gas-fired power because of the lack of recent experience and resulting uncertainty among investors. Without this 'risk premium', nuclear power's estimated levelized cost of electricity (LCOE) would be comparable to the LCOEs for coal- and gas-fired power, even without fees or taxes on carbon dioxide emissions and even with an overnight cost of $4000/kW(e). US policy currently provides for loan guarantees and production tax credits for a limited number of new nuclear power plants, and these act to offset the risk premium. But the study concludes that long-term expansion of nuclear power in the USA will require permanent elimination of the risk premium, which can only be done by demonstrated successful performance.

51. A second study, by Citigroup Investment Research, estimated overnight costs for generic new nuclear reactors in the UK at $3700–$5200/kW(e). This falls within the range of the cost estimates for specific European projects reported in Figure A-3. Figure A-3 also includes cost estimates reported in the recently published study by the OECD/IEA and OECD/NEA, *Projected Costs of Generating Electricity: 2010*. The study concluded that the overnight cost estimates vary substantially across countries due to differences in financial, technical and regulatory conditions. Lower cost estimates were reported from Asia, notably $1556/kW(e) from the Republic of Korea, which has brought four new reactors on-line since 2000 and has six under construction.

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[6] The graph reflects 85 overnight cost estimates, 26 of which are for North America, 32 for Europe and 27 for Asia.

[7] Massachusetts Institute of Technology, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (2003). Available at: http://web.mit.edu/nuclearpower/

A.4.2. Safety[8]

52. Safety indicators, such as those published by the World Association of Nuclear Operators (WANO) and reproduced in Figs A-4 and A-5, improved dramatically in the 1990s. In recent years, in some areas the situation has stabilized. However, the gap between the best and worst performers is still large, providing substantial room for continuing improvement.

53. More detailed safety information and recent developments related to all nuclear applications are presented in the Agency's *Nuclear Safety Review for the Year 2009* (GC(54)/INF/2).

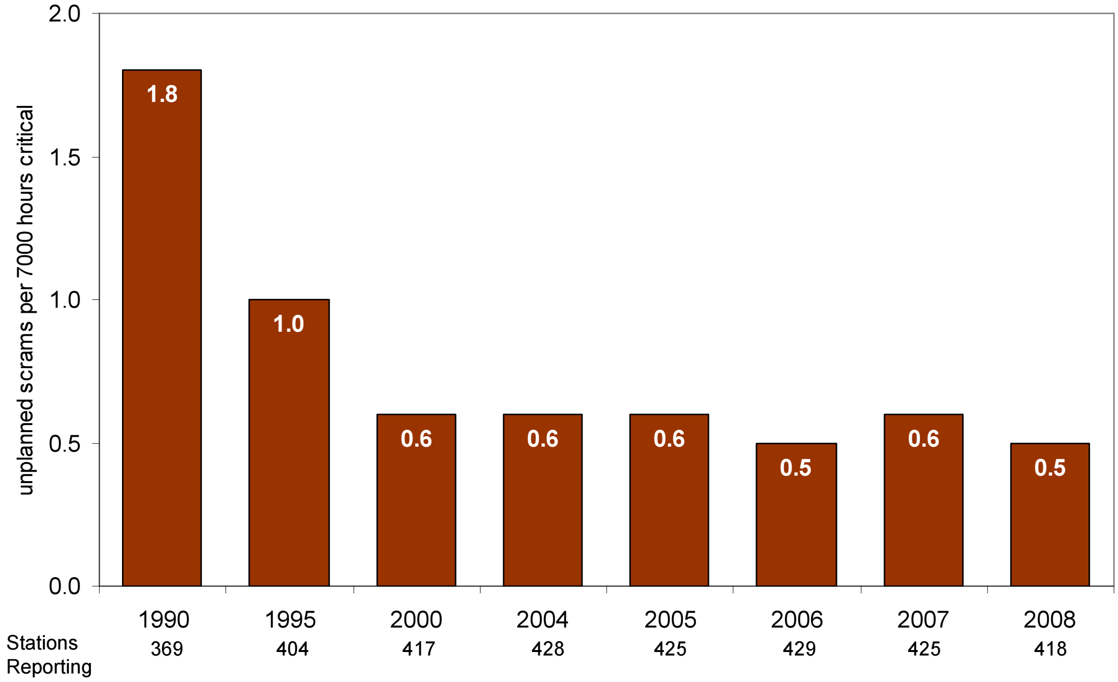

FIG. A-4. Unplanned scrams per 7000 hours critical (source: WANO 2008 Performance Indicators).

[8] 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/Anrep2009/index.html) and at http://www-ns.iaea.org/.

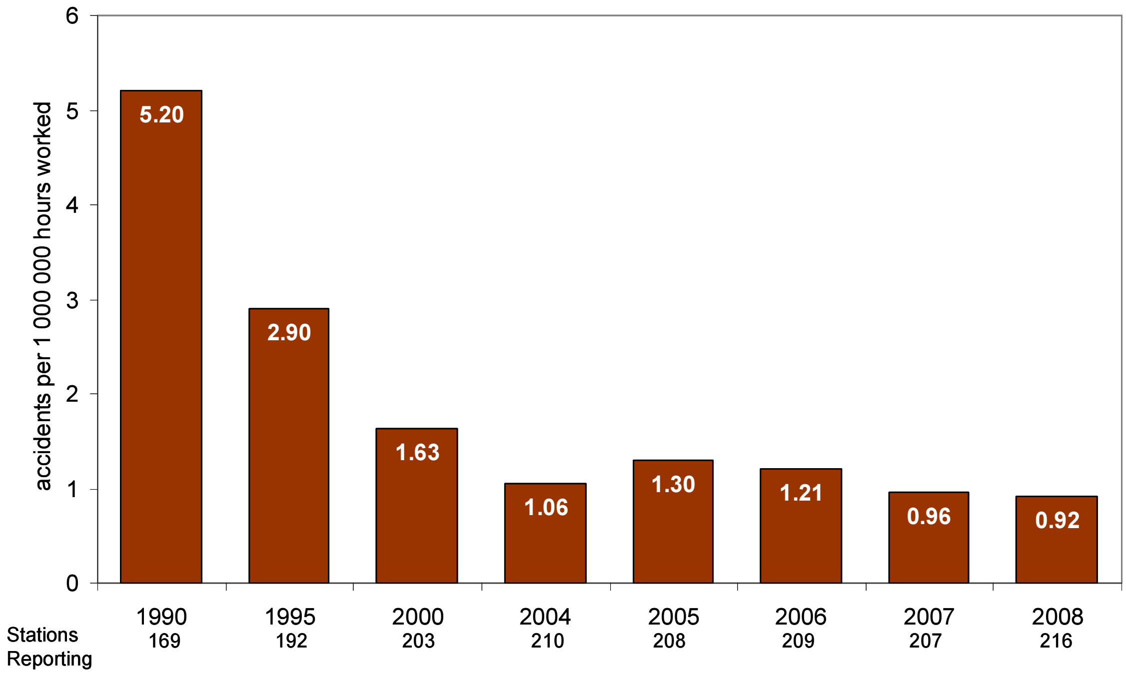

FIG. A-5. Industrial accidents at nuclear power plants per 1 000 000 person-hours worked (source: WANO 2008 Performance Indicators).

A.4.3. Human resource development

54. Estimates of the human resource (HR) requirements associated with any of the projections discussed in Section A.2 are not readily available, and data are scarce on the number of people today with the various skills needed in the nuclear industry and on the number in relevant education and training programmes. With increased interest in nuclear power, concerns have been expressed about possible shortages of people with the skills needed by the nuclear power industry, although it has also been recognized that the situation varies across countries due to a variety of factors, most importantly the strength of their nuclear power programmes.

55. Concerns about possible shortages have prompted initiatives by government and industry to attract students and expand education and training in nuclear related fields. Where data are available, these initiatives appear to be successful. For example, Électricité de France (EDF) recruited four times as many professionals in 2008 as it had in 2006, and it expects to maintain this higher level of recruitment for several more years, supported partly by an internal 'skills renewal' project. AREVA hired 8000 engineers in 2009 and plans to recruit several thousands more over the coming years. Both companies will benefit from a presidentially initiated French Committee to Coordinate Training in Nuclear Science and Technology (C2FSTN), established in 2008. In the USA, nuclear engineering enrolment has increased by 46% in the past five years, assisted by Government funding and biennial surveys of HR needs that have increased the visibility of nuclear careers. China is developing a five-year plan to recruit 20 000 new engineers for its nuclear power programme by 2020, and the Nuclear Power Corporation of India is expanding its existing recruitment programmes to more than double its workforce of engineers by 2017.

56. If the higher projections for nuclear power described in Section A.2 are realized, these efforts will have to be successful and replicated several times over. That challenge will be significant. The Agency's high projection, for example, would require bringing online an average of 22 new reactors each year through 2030. This is much higher than the average of 3 new reactors connected to the grid each year from 2000 through 2009, and one third higher even than the average of 16 new reactors each

year during the 1970s. Still, even in the high projection, nuclear power capacity grows just 0.5% faster than overall electricity generation capacity. This means that human resource needs for nuclear power would be growing only slightly faster than HR needs for electricity generation from coal, natural gas and renewables. The challenge faced by nuclear power is not exceptional.

57. To meet the challenge, however, better numbers are needed:

- for estimating workforce requirements in different countries for design, regulation, manufacture, construction, operation and support of nuclear power plants;
- for estimating the capacity of existing programmes to meet those requirements; and
- for estimating the investments and lead times necessary to expand existing education and training programmes to fill any projected workforce gaps.

58. Efforts to compile information on human resource requirements are currently being undertaken by the OECD/NEA, which focuses on OECD trends following its 2000 report entitled *Nuclear Education and Training: Cause for Concern?*, and the European Nuclear Energy Forum. However, assembling and analysing the data to obtain more comprehensive conclusions on the issue of human resources for nuclear power at the global level requires a coordinated international effort. Accordingly, the Agency, in cooperation with the OECD/NEA, WANO, World Nuclear Association, the Nuclear Energy Institute and Los Alamos National Laboratory in the USA, Japan Atomic Energy Agency, Cogent Sector Skills Council in the UK and others, announced in March 2010 at the International Conference on Human Resource Development for Introducing and Expanding Nuclear Power Programmes, held in Abu Dhabi the launch of a new international initiative. It is planned that, as a result of this initiative, the following activities will be undertaken at a global scale: a survey of human resources at existing nuclear power plants, including contractors and suppliers; a survey of the demand and supply of human resources for nuclear regulatory bodies; a survey of educational organizations and programmes that support nuclear power; the development of workforce planning tools for countries considering or launching new nuclear power programmes; and integration of the above into an accessible database that can be used to model global or national supply and demand of human resources.

B. Advanced Fission and Fusion

B.1. Advanced fission[9]

B.1.1. INPRO and GIF

59. The Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) provides a forum in which technology holders and users jointly consider innovative nuclear energy systems. Since its establishment in 2001, INPRO has grown to 31 members representing 75% of the world's GDP and 65% of the world's population. In 2009, INPRO's activities were consolidated into five new substantive areas: nuclear energy system assessments (NESA) using the INPRO methodology; global vision, scenarios and pathways to sustainable nuclear development; innovations in nuclear technology; innovations in institutional arrangements; and the INPRO dialogue forum on nuclear energy innovations.

60. In 2009, Belarus started a new NESA. A nine-volume user manual for the INPRO methodology was published, and INPRO introduced a 'NESA support package' including training, support missions, and help with implementation, analysis and the evaluation of results. Publications were also issued on *IAEA Tools and Methodologies for Energy System Planning and Nuclear Energy System Assessments* and *Common User Considerations by Developing Countries for Future Nuclear Energy Systems*. INPRO concluded studies on global scenarios and regional trends of nuclear energy development in the 21st century, and on legal and institutional issues of transportable nuclear power plants.

61. The Generation IV International Forum (GIF), through a system of contracts and agreements, coordinates research activities on six next generation nuclear energy systems selected in 2002 and described in *A Technology Roadmap for Generation IV Nuclear Energy Systems*: gas cooled fast reactors (GFRs), lead cooled fast reactors, molten salt reactors, sodium cooled fast reactors (SFRs), supercritical water cooled reactors (SCWRs) and very high temperature reactors (VHTRs). Most ongoing design work on the individual systems, however, is not part of the GIF programme. GIF currently has 13 members.[10]

62. By the end of 2009, nine GIF members had signed the *Framework Agreement for International Collaboration on Research and Development of Generation IV Nuclear Energy Systems*: Canada, China, Euratom, France, Japan, Republic of Korea, South Africa, Switzerland and USA. The framework agreement defines GIF's mechanisms for collaboration, i.e. system arrangements and project arrangements. System arrangements are in place for four of the six selected systems: GFRs, SCWRs, SFRs and VHTRs. In 2009, China's Ministry of Science and Technology joined the system

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[9] More detailed information on IAEA activities concerning advanced fission reactors is available in relevant sections of the IAEA Annual Report 2008 (http://www.iaea.org/Publications/Reports/Anrep2009/index.html). See also INTERNATIONAL ATOMIC ENERGY AGENCY, *Terms for describing new, advanced nuclear power plants*, IAEA-TECDOC-936 (1997); *Status of liquid metal cooled fast reactor technology*, IAEA-TECDOC-1083 (1999); *Current status and future development of modular high temperature gas cooled reactor technology*, IAEA-TECDOC-1198 (2001); *Heavy Water Reactors: Status and Projected Development*, Technical Reports Series No. 407 (2002); *Review of national accelerator driven system programmes for partitioning and transmutation*, IAEA-TECDOC-1365 (2003); *Status of advanced light water reactor designs: 2004*, IAEA-TECDOC-1391 (2004); *Status of innovative small and medium sized reactor designs: 2005*, IAEA-TECDOC-1485 (2005); *Status of Small Reactor Designs Without On-Site Refuelling*, IAEA-TECDOC-1536 (2007); *Liquid Metal Cooled Reactors: Experience in Design and Operation*, IAEA-TECDOC-1569 (2007); and *Advanced Applications of Water Cooled Nuclear Power Plants*, IAEA-TECDOC-1584 (2008).

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

arrangement for SFRs, and a fourth project arrangement for SFRs, on safety and operation, came into effect.

63. The Agency and GIF cooperate to avoid duplication and create synergy. Cooperation includes the use of GIF's economic evaluation model ECONS by the Agency to estimate the costs of gas cooled reactors and the use by GIF of the Agency's economic evaluation model for nuclear generated hydrogen, HEEP. GIF also cooperates in the Agency's coordinated research project on heat transfer behaviour and thermohydraulics code testing for supercritical water cooled reactors.

B.1.2. International Framework for Nuclear Energy Cooperation (IFNEC)

64. The International Framework for Nuclear Energy Cooperation (IFNEC) was originally launched by the USA in 2006 as the Global Nuclear Energy Partnership (GNEP). It has included (a) a cooperative effort by now 25 countries who agree on the necessity of expanding nuclear energy around the world and (b) a US domestic programme aimed at deploying recycling, fuel fabrication and reactor technologies to destroy long-lived radioactive elements in spent fuel. While the US domestic programme was discontinued in 2009, the international cooperative effort continued, with meetings of its two working groups – on reliable fuel services and on infrastructure development – as well as its Steering Group in April and its ministerial level Executive Committee meeting in October in China. The name of the international cooperative effort was changed in June 2010 as part of a transformation to provide a broader scope with wider participation.

B.1.3. Additional Development of Advanced Fission

65. In addition to INPRO, GIF and IFNEC, a number of countries, companies and partnerships are researching, developing and deploying advanced fission reactors. These efforts constitute the majority of the work around the world on advanced fission and cover high temperature reactors, fast reactor systems, and improved light water reactors spanning a range of sizes and applications. Developments in 2009 were very much a continuation of the progress that was summarized in the *Nuclear Technology Review 2009*[11] and will be described in more detail in the Agency's forthcoming 2010 update of the *International Status and Prospects of Nuclear Power*.

B.2. Fusion

66. Work on infrastructure and site preparation for the International Thermonuclear Experimental Reactor (ITER) progressed as planned by the seven ITER parties (China, India, Japan, Republic of Korea, Russian Federation, USA and European Union). Site preparations were completed in March. Procurement arrangements have been signed for facilities worth approximately €1.5 billion, about a third of the total anticipated procurements.

67. Through their formal Cooperation Agreement[12], the Agency and the ITER Organization began planning international cooperation on training, personnel exchanges, conferences, and publications on fusion components and installations. The involvement of young fusion and plasma physicists, with Agency support, in joint experiments (and subsequent publications) on fusion at existing facilities continued with experiments organized in May by the Brazilian tokamak community on turbulence phenomena in tokamak plasmas that degrade energy confinement.

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[11] See *http://www.iaea.org/Publications/Reports/ntr2009.pdf*.

[12] Reproduced in document INFCIRC/25/Add.8 available on the Agency's website at http://www.iaea.org/Publications/Documents/Infcircs/2009/infcirc25a8.pdf.

68. Construction of the National Ignition Facility (NIF) at the Lawrence Livermore laboratories in the USA was completed, and NIF was inaugurated in May. It has 192 lasers with a total energy of approximately 1.5 megajoules to produce radiation in a 'hohlraum' to ignite fusion in deuterium-tritium pellets. Initial results on the beam interactions within the hohlraum were reported in September at the International Conference on Inertial Fusion Sciences and Applications and showed the readiness of NIF to start performing physics experiments relevant both to eventual energy production using inertial fusion and to better understanding the nature and evolution of the universe.

C. Atomic and Nuclear Data

69. The major nuclear databases developed by the International Network of Nuclear Reaction Data Centres and the International Network of Nuclear Structure and Decay Data Evaluators, coordinated by the Agency, are continuously improved with respect to the quality and completeness of the data, their visual presentation and their global distribution. Of particular note in 2009 was the international collaboration on quality assurance for the principal experimental nuclear reactions database (EXFOR). New data libraries for applications in fast reactor calculations, neutron dosimetry and material analysis with ion beams were made available. The number of user retrievals from the web servers of the cooperating centres has grown at about 10 per cent per year for the last two years.

70. Advanced treatment planning and physical dosimetry with proton and ion beams rely on computerized models (Monte Carlo techniques) that use nuclear data as an important input. Two new ion beam facilities became operational in Germany and Japan in 2009. More than ten radiotherapy centres are in advanced stages of construction. At the 2009 International Conference on Ion Beam Analysis, new uses of ion beams were reported for molecular imaging and studying nanoparticles and nanoscale devices, in microtomography, and for ion beam analysis on the surface of Mars.

71. With respect to nuclear power, efforts within the European nuclear industry focused on validating the new Joint Evaluated Fission and Fusion Library version 3.1.1 (JEFF-3.1.1) in order to adopt it for safety analyses and operational planning of the current reactor fleet and for analysing generation IV reactor designs. For fusion, the *Handbook of Activation Data Calculated Using EASY-2007* was published, condensing more than 20 years of nuclear reaction data studies relevant to fusion devices. Atomic and molecular data crucial for the ITER project are being compiled in databases worldwide, in particular with regard to processes involving light elements in the divertor and edge plasma regions. These new databases include data on excitation, ionization, recombination and particle collision processes.

D. Accelerator and Research Reactor Applications

D.1. Accelerators

72. There are approximately 163 low-energy electrostatic accelerators located in over 50 Member States, 9 spallation neutron sources distributed over 5 Member States and 50 synchrotron light sources located in over 20 Member States. The number of low-energy electrostatic accelerators worldwide is essentially constant, with retirements in developed countries being counterbalanced by new

accelerators in developing countries for nuclear analytical services. The numbers of spallation neutron and synchrotron light sources are growing by a few machines per decade

73. Modern accelerators are used in the fields of medical radiation physics, radiation biology, experimental nuclear physics, agriculture, sterilization processes, material research, studying cultural artefacts and environmental protection. Given the human resources challenges in nuclear science and technology (see Section A.4.3), small accelerators are also increasingly incorporated in nuclear science and technology academic curricula to help develop students' general and subject-specific skills. In 2009, for example, Ghana established a National Accelerator Facility to further strengthen institutional capacity to support research and human resource development. Small accelerators, in particular, provide opportunities to acquire hands-on knowledge and experience, opportunities usually not available at larger facilities.

74. Spallation neutron source targets used on high power accelerators provide useful information on radiation damage in accelerator-driven systems, including those envisaged for nuclear waste transmutation and power generation. In 2009, the liquid metal target in the Megawatt Pilot Target Experiment (MEGAPIE) at the Swiss Spallation Neutron Source (SINQ), which was irradiated at a power level of 0.8 MW for five months in 2006, began to be dismantled. The target structural materials are being separated and dissected into samples for testing the properties of the irradiated material by MEGAPIE's international partners. The information gained will assist in the design of future long lived, high power targets in accelerator-driven systems.

D.2. Research reactors

75. Research reactors can have multiple uses: training in nuclear sciences, nuclear research, material testing, radioisotope production for industry and medicine, and commercial services such as silicon doping, neutron activation analysis, gem improvement and non-destructive testing. And they can be a step in a national programme to introduce nuclear power. With the growing interest in nuclear energy, more than 20 Member States are now considering building new research reactors. In 2009, the Eastern European Research Reactor Initiative coalition, supported by the Agency, launched a group fellowship training course to assist Member States interested in starting a first research reactor project. The course provides training related to planning, evaluation, development, construction, commissioning, utilization, operation and maintenance of research reactors.

76. There are more than 240 operational research reactors around the world. There were no new research reactors commissioned in 2009. As older reactors are retired and replaced by fewer, more multipurpose reactors, the number of operational research reactors is expected to drop to between 100 and 150 by 2020. Greater international cooperation will be required to assure broad access to these facilities and their efficient use. Cooperative networks will also be helpful for upgrading existing facilities and developing new facilities. Progress on building such networks (in the Mediterranean, Eastern Europe, Caribbean and Central Asia regions, plus a topical network on residual stress and texture analysis) continued in 2009, but extensive additional work will still be needed.

77. The US Global Threat Reduction Initiative (GTRI) provides the framework for one of the major efforts in converting research reactor fuel, and targets used in isotope production facilities, from highly enriched uranium (HEU) to LEU. In 2009, the programme's scope was expanded from 129 research reactors to 200. By the end of April 2010, 72 research reactors around the world that had been operating with HEU fuel had converted to the use of LEU fuel or had shut down before conversion, and another 33 had been identified for which conversion is potentially feasible with existing qualified LEU fuels. High performance research reactors will need new high density fuel under development to convert (see paragraph 79 below). With respect to the conversion, from HEU to LEU, of targets used in the production of molybdenum-99, South Africa, which fully converted the Safari-1 reactor to LEU

fuel in 2009, became the first large scale molybdenum-99 producer to report substantial progress on also converting medical isotope production targets to LEU.

78. The GTRI's Russian Research Reactor Fuel Return (RRRFR) programme made significant progress in 2009. Approximately 270 kg of HEU spent nuclear fuel and 49 kg of fresh HEU nuclear fuel were shipped back to the Russian Federation from Hungary, Kazakhstan, Libya, Poland and Romania. Since its inception, the programme has successfully returned approximately 1350 kg of HEU, including fresh and spent nuclear fuel, to the Russian Federation.

79. Very high density advanced uranium–molybdenum fuels that are currently under development are required for the conversion of high flux and high performance research reactors. In this regard significant progress has been made in the past few years. Uranium–molybdenum fuel behaviour and performance are being investigated collaboratively by an International Fuel Development Working Group that includes Argentina, Belgium, Canada, Chile, France, Germany, the Republic of Korea, the Russian Federation and the USA. In the USA, efforts are focused on the development of monolithic uranium–molybdenum fuel for use in high flux research reactors. Significant advances are taking place as fabrication technology matures. A new European initiative was consolidated in 2009 to qualify very high density LEU dispersed uranium–molybdenum fuel for conversion to LEU of high flux European reactors.

80. Although substantial progress in uranium–molybdenum fuel development and qualification was made in 2009, further progress and significant testing are needed to achieve the timely commercial availability of very high density qualified LEU fuels.

E. Nuclear Technologies in Food and Agriculture

E.1. Improving livestock productivity and health[13]

81. The analysis of animal genetic resources has been identified by the Food and Agriculture Organization of the United Nations (FAO) and the World Organisation for Animal Health (OIE) as a high priority area since it provides crucial options for the sustainable development of livestock production and for enhancing food security. With support from the IAEA, important progress has been made in the analysis of genetic diversity in cattle, sheep and goat breeds, to improve the selection of desirable animals for higher productivity as their ability to resist endemic diseases or harsh environments is in many cases linked to their genetic make-up. The data and results from such genetic analyses are valuable for ensuring the sustainability of future animal breeding programmes and their ability to select animals that carry suitable genes. However, there are significant gaps in capacity for using the genetic data from these analyses for animal breeding programmes, particularly in developing countries. To this effect, a computer network system interface was developed to make available the genetic data to all Member States, and to provide access to laboratory protocols, standard operating procedures for gene analysis, tools for genome searches, and a livestock molecular markers database[14].

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[13] Additional information is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2009/index.html) or at http://www.iaea.org/About/Policy/GC/GC54/Agenda/index.html).

[14] *Development of RT-db (Real Time Database) for Quantitative Trait Loci (QTL)/Genes/DNA Sequences and Genetic Characterization in Small Ruminants* (http://www.intl-pag.org/16/abstracts/PAG16_P08a_852.html)

Genomic and phenotypic data have been acquired from over 4000 sheep and goats of 89 breeds. This data will be used to identify common genes that could be exploited for improving animal production.

82. Radio-labelled nucleotide probes have contributed to the sequencing of the full bovine genome[15]. These tools provide a means for the selection of more energy-efficient animals with a smaller environmental footprint, and in particular animals that produce less greenhouse gas emissions. This discovery could lead to more efficient meat and milk production, and provides new information about the evolution of mammals as well as on cattle-specific biology. It also indicates the direction for research that could result in more sustainable food production in a world challenged by global population growth.

83. The early and rapid diagnosis of veterinary diseases by using nuclear techniques combined with modern biotechnology is critical in efforts to limit impacts on both animals and humans as well as to improve food security. The high sensitivity and specificity of nuclear technologies together with modern biotechnology can be used for the specific detection of animal disease pathogens before they cause a disease, for the tracing of an animal's genetic fingerprint and for the characterization of microorganisms that affect animal and human health. For example, nuclear molecular technologies allow for the confirmatory diagnosis of Avian Influenza and Swine flu within one day, while classical diagnosis of the two diseases can take up to one week.

FIG. E-1. Indigenous goats from Myanmar, resistant to parasitic diseases and well adapted to the local environment, which were part of a genome-mapping exercise using nuclear technologies.

E.2. Insect pest control

84. In the field of insect pest control, the use of nuclear techniques is not confined to the application of gamma irradiation for insect sterilization as part of the area-wide application of the sterile insect technique (SIT) and related genetic control methods, but also includes the use of isotopes for studies on insect biology, behaviour, biochemistry, ecology and physiology. The Agency has also been

[15] The Bovine Genome Sequencing and Analysis Consortium, Christine G. Elsik, Ross L. Tellam, and Kim C. Worley. The Genome Sequence of Taurine Cattle: A Window to Ruminant Biology and Evolution Science 24 April 2009 324: 522-528.

involved in the use of radionuclides for entomological research to address insect pest problems. The Agency's *Laboratory Training Manual on the Use of Nuclear Techniques in Insect Research and Control*, re-edited and published in 1992, is a major contribution from the Agency in this area. Since the mid-1990s, the global scientific and social environment has changed significantly. From an environmental perspective it is no longer acceptable to release radionuclides with insects into the field. In addition, it has become increasingly expensive to use radionuclides in the laboratory due to safety considerations.

85. Stable isotope methods are a substitute for many radionuclide methods. Such isotopes are non-radioactive, are naturally omnipresent in the environment, and personnel face no adverse health risks when handling them. With few safety considerations to address, specialized regulations with regard to buildings and equipment are not required. These factors all help to reduce costs and facilitate the use of stable isotopes, and enable the safe release of insects labelled with such isotopes into the environment.

86. In 2009, the Agency and the FAO published the *Manual for the Use of Stable Isotopes in Entomology*, which introduces the basic principles and techniques of stable isotope science and reviews the use of stable isotopes in entomological research. Advances in isotope ratio mass spectrometry in terms of detection, accuracy and automation have broadened experimental possibilities immensely over the past 25 years. Natural processes in the biosphere lead to distinctive isotopic signals and stable isotopes can therefore be extremely useful in entomological research to answer many biological and ecological questions such as tracing insect movement, feeding patterns in the food chain, and nutrient and sperm transfer, and answering specific questions about resource usage.

87. On the other hand, one of the main disadvantages of using stable isotopes is the capital cost of isotope ratio mass spectrometers. In addition, the equipment requires a temperature controlled environment and skilled personnel to maintain and service the sensitive instrumentation. These issues may be overcome by contracting out isotope analysis to a commercial analysis laboratory. There are now many laboratories which offer isotope analysis on a pay per sample basis, and it is simple, safe and inexpensive to ship stable isotope samples across the world.

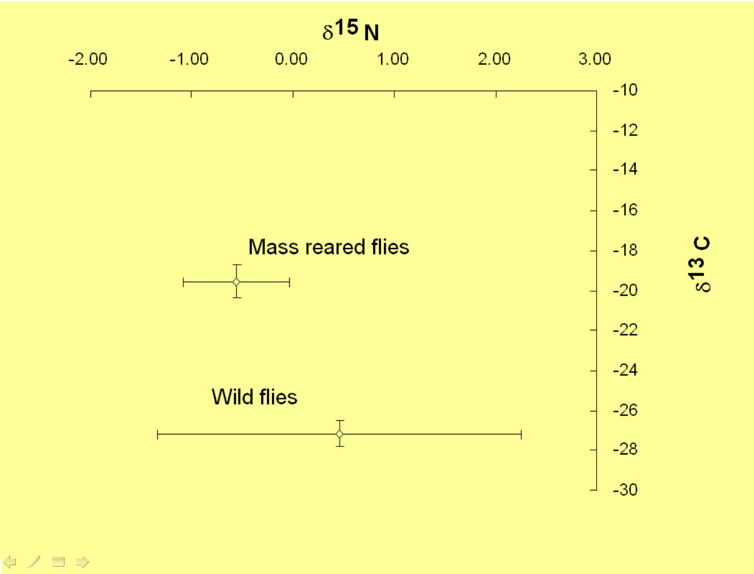

FIG. E-2. The signature of stable isotopes can be used to distinguish released mass-reared laboratory flies from wild flies for pest population monitoring purposes as part of the implementation of sterile insect technique programmes. This figure shows the mean isotopic signatures of male Ceratitis capitata flies from the field and from a mass rearing facility; the bars are plus/minus standard deviation from the mean values.

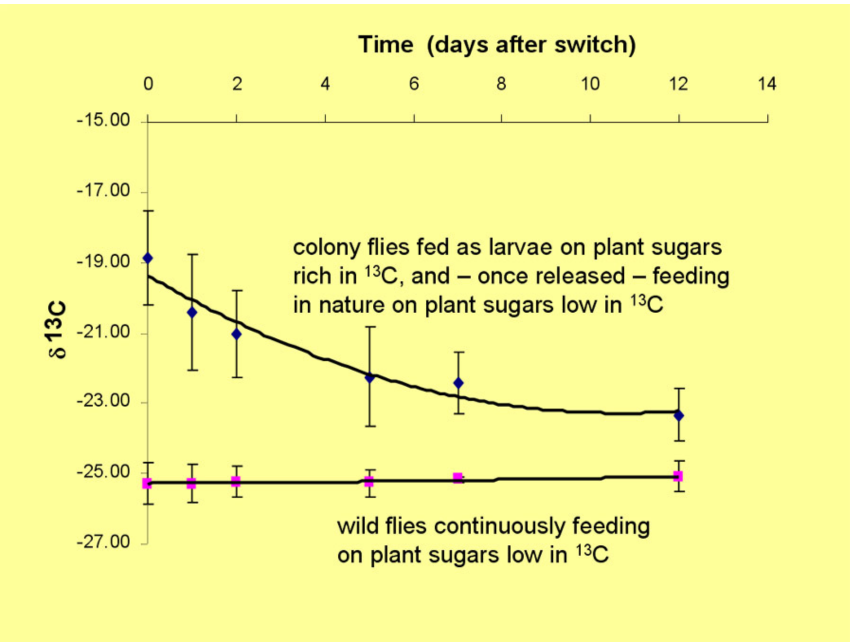

FIG. E-3. The isotopic signature of mass-reared flies persists throughout their lives, even when the flies are released on day 0 when they switch from a larval diet high in carbon-13 to an adult diet low in carbon-13 mimicking sterile insect technique practice. It is possible to distinguish sterile from wild flies with greater than 99% certainty.

E.3. Food quality and safety

88. Food irradiation is a valuable technique to control microorganisms, including those that cause a range of food-borne diseases. Outbreaks of food-borne diseases have been associated with all types of foods and pathogens can be transferred to foods from different sources of contamination that arise from product handling, processing and preparation.

89. As prolonged heating is not an appropriate treatment for all foodstuffs, food irradiation is an alternative approach for food processing and treatment. One of the significant advantages of irradiation technology is that it destroys microorganisms without significantly increasing temperature. Irradiation can be applied to fresh vegetables, fruits and frozen foods with no significant change to taste or texture. It can also be used to treat foods that have been cooked conventionally and packaged ready for distribution to consumers. Another advantage of irradiation is that it destroys spoilage-causing organisms, helping to keep meat, poultry and seafood fresh for longer.

90. Most previous research and development activities on irradiated foods have focused on processing simple commodities for consumption by the general public. However, recent developments indicate a potential need for applications of food irradiation to achieve exceptional levels of microbiological safety for specific target groups of consumers that are very sensitive to microorganisms in their diet and require a secure supply of safe and wholesome food. For example, those with compromised immune systems are especially sensitive to food-borne bacteria that often limit the range of foods they can eat. To meet demanding requirements of the medical community, a range of irradiated foods intended for special dietary purposes could be researched and developed through the use of irradiation.

FIG. E-4. The US Food and Drug Administration has recently approved the irradiation of spinach due to outbreaks of bacteria.

91. The next steps in the further application of food irradiation are to develop and improve irradiation techniques in conjunction with other food processing technologies that are suitable for a broad range of foods. In particular, these foods must be suitable for consumption by specific target groups where exceptional levels of food hygiene are necessary. The application of irradiation alone, or in combination with other food technologies, will continue to be used to develop safe foods for nutritional, microbiological and acceptability testing, thereby contributing to improved human health.

E.4. Crop improvement

92. There is a renaissance in the use of mutation induction for crop improvement and in support of fundamental research. Two novel techniques being developed are ion beam implantation, which allows an isotope to decay *inside* the cell, and space (the region beyond the earth's atmosphere) breeding, where cosmic rays flow *through* the cell, complementing other techniques used in plant mutation breeding. Worldwide, the number of officially released mutant varieties for commercial production, stemming from 170 different plant species, is increasing steadily and approaching 3100[16]. In the meantime, new facilities for mutagenic treatment, such as ion beam implanters, gamma phytotron, and gamma greenhouse, are being constructed and applied to mutation breeding in some Asian countries.

93. In parallel, new frontiers are being crossed in the development of novel technologies for the rapid and large-scale discovery of different types of induced mutation. On the molecular level, the trend is towards the development of technology packages combining modern biotechnology such as high throughput screening technologies and next generation sequencing with mutation induction. Systematic, high throughput, phenotypic screening techniques based on automated image analysis tools and robot facilities, as currently performed in the High Resolution Plant Phenomics Centre, Australia, can handle very large mutant collections (i.e. 10 000–100 000 fully phenotyped plants) and bridge the so-called 'phenotype/genotype gap'. This type of screening is vitally important because it allows the plant breeder to efficiently identify a valuable mutant line with the characteristics to produce more, even in adverse conditions. Finding a way to fill the gulf between the available mutant resources and the full range of plant phenotypes is essential in order to exploit the full potential of plant biodiversity including major crops under investigation. Enhancements in efficiency through gene-based mutation breeding can assist in improving both the quality and availability of crop varieties, thereby increasing food supply to enable a much-needed decline in food prices. It is now possible for a genome to be sequenced at an economical cost that is within the reach of a low income country.

E.5. Sustainable land and water management

E.5.1. Improving agricultural water management using isotopic methods

94. Soil water available for crop growth is dependent on the extent of water loss from bare soil (i.e. evaporation) and plant leaf transpiration. To improve irrigation water use efficiency, it is important to quantify these two water loss components. However, evaporation and transpiration are difficult to measure accurately on a field scale, owing to complex interactions with other factors such as rainfall intensity, soil water status, plant rooting depth and land cover. Stable water isotopes (oxygen-18 and hydrogen-2) can be effectively used to unravel such interactions since they are natural tracers of water movement within the soil–vegetation–atmosphere continuum. Soil evaporation results in the enrichment of soil water isotopic composition in oxygen-18 and hydrogen-2. In contrast, plant transpiration does not affect soil water isotopic composition. Recent research quantifying evaporation and transpiration using stable water isotopic techniques has been successfully carried out in semi-arid grasslands, coniferous forests and cropping systems. The information obtained will be used to develop technology packages and models to improve land and water management in different environments.

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[16] See the Mutant Variety and Genetic Stock Database at http://mvgs.iaea.org/

FIG. E-4. Measuring soil evaporation and plant transpiration from a maize field using conventional and isotopic techniques (courtesy of Prof. Xurong Mei).

E.5.2. Soil organic carbon sequestration and climate change mitigation

95. Soil organic carbon (SOC) sequestration has the potential to attenuate increasing atmospheric carbon dioxide (CO_2) levels and mitigate climate change. Through photosynthesis, plants use CO_2 to grow. When plants die and decompose, some of the plant carbon is sequestered in the soil as SOC. While significant progress has been made in assessing SOC, the control and regulation mechanisms of SOC fluxes in the soil are not yet fully understood. In particular, the link between SOC sequestration and soil nitrogen and phosphorus availability is not well identified. Through the use of radioactive (carbon-14) and stable (carbon-13) carbon isotopes together with soil carbon fractionation and mesocosm (soil monoliths) techniques, both nitrogen and phosphorus availability were found to play a critical role in determining the extent of SOC sequestration capacity and the partitioning of SOC into different soil pools with different sink potentials. In order to improve the much needed SOC sequestration models as an instrument for climate change mitigation, it is necessary to assess SOC sequestration in response to nitrogen and phosphorus changes in agro-ecosystems where land rehabilitation is increasingly important for sustainable food production. Such information is very important so that agriculture is considered in future carbon trading schemes and to reduce carbon emissions[17, 18].

F. Human Health

F.1. Combating malnutrition with nuclear techniques

96. Micronutrient deficiencies, the ‘hidden hunger’, affect a large proportion of the global population, particularly infants, children and women of child-bearing age in developing countries.

[17] See also Trumbore, S. 2009. *Radiocarbon and soil carbon dynamics*. Annual Review of Earth and Planetary Sciences 37:pp. 47–66.

[18] Bradford, M., Fierer, N., Jackson, R., Maddox, T., Reynolds, J., 2008. *Nonlinear root-derived carbon sequestration across a gradient of nitrogen and phosphorous deposition in experimental mesocosms*. Global Change Biology, 14, pp. 1113–1124.

Deficiencies of vitamin A, zinc and iron are major public health concerns as they contribute to impaired growth and cognitive development during early life and to poor health in children.

97. The development of effective, sustainable, food-based strategies to combat micronutrient deficiencies is urgently needed. Food-based strategies include conventional interventions such as food fortification and dietary modification but also more innovative approaches such as nutritionally improved staple foods — 'biofortification'. As an integral part of the development and evaluation of nutritional interventions to combat micronutrient deficiencies, nuclear techniques are used to evaluate bioavailability of micronutrients.

98. The results of recent applications of stable isotope techniques to assess bioavailability of iron and provitamin A carotenoids in vulnerable population groups will assist policy makers, health professionals and other stakeholders, including food industry and plant breeders, on determining the way forward. For example, the overall impact of food fortification strategies to combat iron deficiency will depend on the bioavailability of iron compounds as well as the presence of inhibitors and enhancers of iron absorption in the diet, as emphasized in recent guidelines elaborated by the World Health Organization (WHO) and the FAO[19].

FIG. F-1. Infants, children and women of child-bearing age in developing countries are the most vulnerable population groups at risk of the 'hidden hunger' (Courtesy of Stephanie Good, Ethiopia).

99. Stable isotope techniques to estimate total amounts of vitamin A are currently used to provide new information on the biological value of orange flesh sweet potatoes, which are rich in provitamin A carotenoids.[20] The Agency works closely with international partners such as HarvestPlus in this area as well as in the evaluation of other biofortified stable crops such as high zinc wheat.[21]

100. The importance of these efforts is highlighted in the recent Copenhagen Consensus 2008 report[22]. A panel of eight of the world's most distinguished economists ranked the proposed solutions to global challenges based on economic cost and benefits. Solutions to combat micronutrient deficiencies i.e. supplementation, food fortification and biofortification were ranked as first, third and fifth out of 30 solutions to address the ten different challenges posed by nutrition specialists.

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[19] World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO). *Guidelines on food fortification with micronutrients*. Allen L, De Benoist B, Dary O, Hurrell RF, eds. http://www.who.int/nutrition/publications/micronutrients/9241594012/en/index.html

[20] See http://www.harvestplus.org/content/biofortified-foods-offer-protection-vitamin-deficiency

[21] See http://www.harvestplus.org/content/study-shows-women-absorb-more-zinc-biofortified-wheat

[22] See http://www.copenhagenconsensus.com/The%2010%20challenges-1.aspx

F.2. Hybrid imaging SPECT/CT and PET/CT[23]

101. Diagnostic imaging is one of the most innovative areas of modern medicine. It can be divided into two broad categories: modalities that very precisely define anatomical details, and modalities producing functional or molecular images. In the first category, examples include computed tomography (CT) and magnetic resonance imaging (MRI), which identify structural changes down to the millimetre. Positron emission tomography (PET) and single photon emission computed tomography (SPECT) are examples of the second, investigating diseases down to the molecular level.

102. Over the past decade, technology has enabled anatomical and functional modalities to be merged into hybrid imaging systems such as SPECT/CT and PET/CT. The hybrid imaging systems allow a combined investigation of both the anatomy and the function of human organs. The clinical benefits are numerous and include better identification and localization of lesions combined with better characterization of structural and metabolic changes within the identified lesions. As a result, diseases are detected in their earliest phase with higher accuracy, allowing an early treatment with the highest chance of a complete and quick recovery. Hybrid imaging has been successfully applied in cardiology and cancer. PET/CT is used to evaluate blood flow impairment in coronary artery blockage, which may lead to tissue necrosis. In oncology, hybrid imaging enables the early detection of cancer, demonstrating changes at the cellular level long before anatomical changes appear. In orthopaedic surgery, SPECT/CT and PET/CT are the best imaging modalities for the investigation of lower back pain and may also be used in post-surgical and post-traumatic situations. Other areas of applications of hybrid imaging include the evaluation of benign diseases that affect the brain, thyroid, parathyroid and any other organs of the human body.

[23] Additional information is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2009/index.html) or at http://www.iaea.org/About/Policy/GC/GC54/Agenda/index.html).

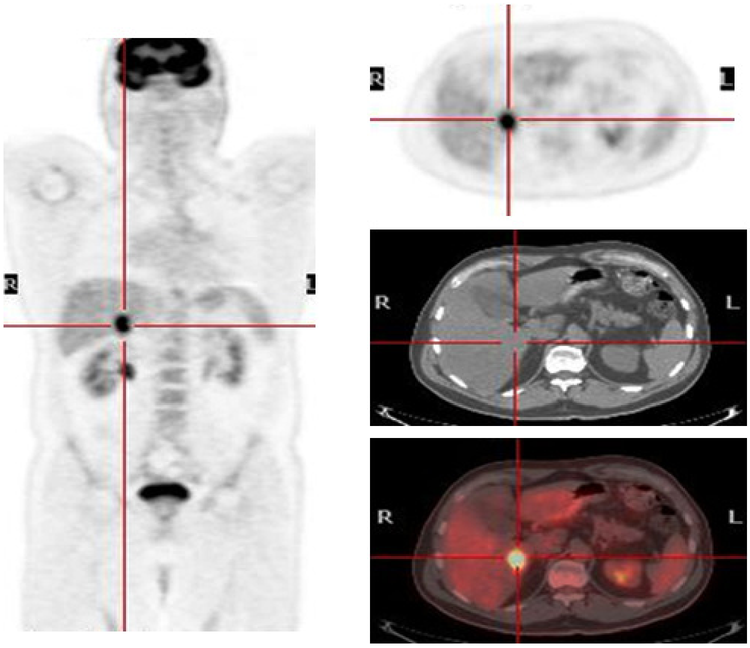

FIG. F-2. Images, such as the one above of the internal organs of a 50 year-old man with a history of colonic cancer that has been surgically removed, are essential in monitoring the evolution of disease. The lighter areas show a rise in tumour marker due to possible tumour relapse. PET/CT shows single liver metastasis without any other lesions, indicating that it could be removed with additional surgery (courtesy of S. Fanti).

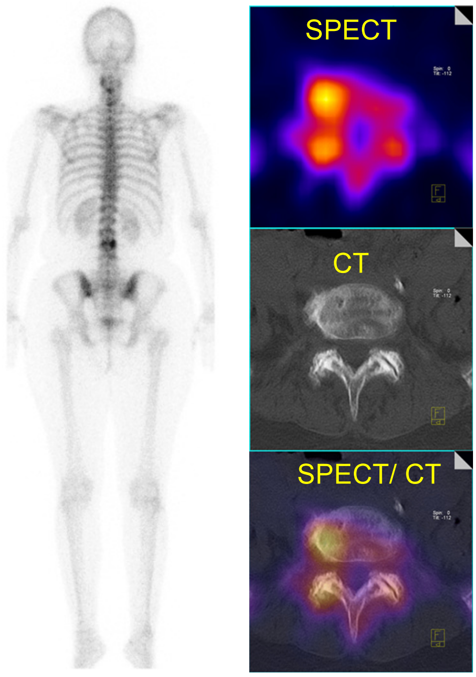

FIG. F-3. A SPECT study shows increased bone metabolism in the lumbar and cervical spine of this 65 year-old woman with a previous history of melanoma. The co-registered SPECT and CT images show massive bone changes in the anatomy associated with degenerative processes. Bone metastases could be ruled out.

F.3. Advances in radiation oncology applications

103. During 2009, several new technological developments emerged in the field of radiation oncology. These were highlighted in April 2009 during the Agency's International Conference on Advances in Radiation Oncology (ICARO)[24].

104. The first important issue concerns efforts to assess the comparative value of cobalt units versus linear accelerators, which is of particular importance to low and middle income countries. During ICARO, and subsequently in a comparative assessment of nuclear technologies in the human health field carried out by the Agency, experts agreed that the choice between these two treatment modalities will depend on several factors including the availability of national cancer control plans, the existence of a required critical mass of qualified scientific and medical staff, as well as the availability of adequate infrastructure.

105. Secondly, issues of uncertainty and accuracy in radiation oncology are becoming more important globally as treatment techniques become more sophisticated, with higher doses being used to improve cancer cure rates. There is an increased appreciation that quality assurance activities and accurate documentation are required at each step of the patient management path. The development of evidence-based clinical guidelines and protocols is being encouraged.

106. New technologies, such as intensity modulated radiation therapy (IMRT), image guided radiation therapy (IGRT), and the use of protons and charged particles, are increasingly being scrutinized to ensure that clinical practice relies on sound scientific evidence. This is of importance not only for low and middle income countries, but also for high income countries, as resources are limited and cost utility measures are increasingly relevant.

107. The use of 'hypofractionated treatment schedules' is also experiencing a resurgence, owing to both cost-cutting efforts as well as the improved accuracy of delivery of high radiation doses with technically advanced equipment.

F.4. Impact of digital technology on radiological X-ray imaging

108. Digital technology advances have facilitated an increase in the application of computed tomography (CT). The use of rapid wide-area multiple-slice CT, for example, has expanded the use of CT to a large range of applications from cardiology to paediatric investigations. Such new technology brings with it increasing radiation doses and challenges our established practices of dose determination. Radiological diagnosis is an area of medicine that is vital to effective health care. On average, every second person in the world has a radiological examination each year. Figure X shows that the number of X-ray radiological examinations has more than doubled in the last 20 years (data based on the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). There is a marked imbalance in the geographical distribution of services — in effect, less than 2% of the total examinations conducted worldwide are in low income countries. Another distinctive current feature of radiology is the rate of technological change, characterized by a dramatic move from analogue images, such as film, to digital imaging techniques.

109. For low income countries, digital technology brings with it unexpected opportunities, as well as challenges. Unfortunately, many developing countries still rely almost completely on manual development of film to produce images for diagnosis. This methodology is technically challenging, often resulting in poor quality images. It is also environmentally unfriendly. Especially critical, however, is the way in which such processing can limit effective service delivery, where radiological

[24] For more information, see http://www-pub.iaea.org/MTCD/Meetings/Announcements.asp?ConfID=35265

equipment and skilled manpower are scarce. Digitized medical images can be sent electronically to distant places, allowing remote or resource limited locations to access centres of excellence for expert diagnosis and to assist in professional training. With the maturing of this technology and further cost reductions, digital imaging appears increasingly financially viable in developing countries. The continuation of improvements in digital technology promises a future alternative to the manual processing of film images, bringing with it the hope of a more efficient and widespread usage of radiological services.

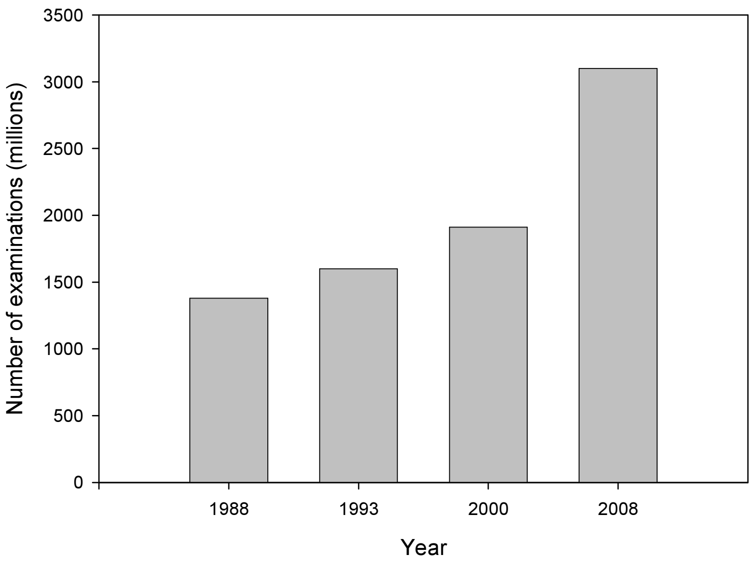

FIG. F-4. Worldwide trend in X-ray radiological examinations (UNSCEAR official records, 2008)

G. Environment

G.1. Nuclear techniques for the quantification of submarine groundwater discharge[25]

110. Water flows from the continent towards the sea in both rivers and aquifers. When aquifers intersect with the shoreline they release fresh water to the ocean. Estimates of this submarine groundwater discharge (SGD) vary significantly between 6% and 100% of freshwater inputs into coastal waters, largely due to the regional and temporal variability of SGD. More recently, SGD has received considerable attention in the area of coastal management due to its potential as a freshwater resource in areas with water shortages. Additionally, if SGD is composed of brackish water it may be utilized in desalination plants. On the other hand, SGD may also contain high levels of pollutants (nutrients, metals, pesticides) thus affecting coastal ecosystems. This can result in outbreaks of harmful algal blooms and the contamination of coastal regions. Finally, as a management tool,

[25] Additional information is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2009/index.html) or at http://www.iaea.org/About/Policy/GC/GC54/Agenda/index.html).

knowledge of the volume of submarine groundwater discharge helps to prevent overexploitation of coastal aquifers and prevent salt water intrusion.

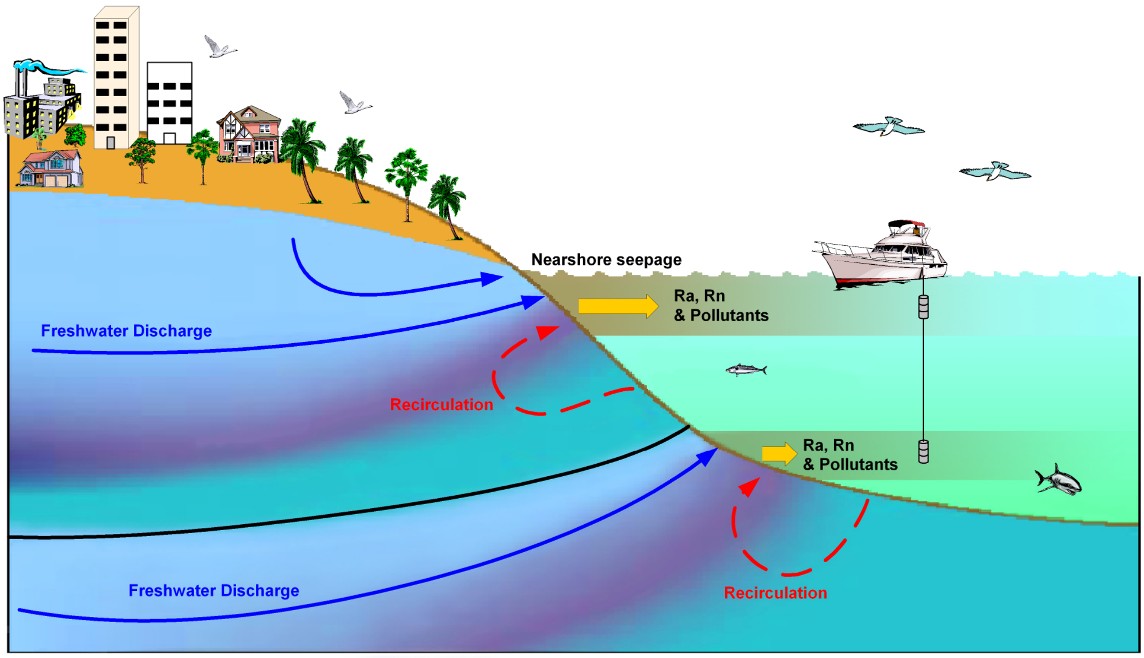

FIG. G-1. A depiction of the concept of submarine groundwater. The hydraulic gradient causes fresh water to discharge into the sea. Recirculation of seawater driven, for example, by tides contribute to SGD.

111. Radium and radon measurement techniques have been developed to detect and quantify SGD in coastal regions;[26] both radionuclides are enriched in SGD relative to sea water. Sources of SGD can be detected by measuring the spatial distribution of radium and radon in coastal waters. Temporal changes in their concentrations — mainly a result of mixing between SGD and seawater driven by the tides — allow for the volume of SGD to be determined. Moreover, the determination of four radium isotopes (radium-223, radium-224, radium-226 and radium-228) helps to understand the dispersion and mixing time scales of SGD in coastal waters. Given the ease in the application of radon and radium as tracers of SGD, their use is expected to increase in coastal areas under environmental pressure.

G.2. Understanding the carbon cycle: applying nuclear techniques in assessing particle fluxes from ocean to seafloor

112. A fundamental and outstanding issue in marine biogeochemistry is the understanding of the mechanisms that control and enhance the flux of material from the ocean surface to the seafloor or depth. The ocean is a major carbon sink and the trapping of increasing quantities of CO_2 is provoking its acidification. ‘Sinking particles’ are the ultimate removal mechanism of carbon and other elements as well as contaminants from the upper ocean. This includes atmospheric carbon, which is converted from CO_2 to biomass and sequestered to deepwater via particle sinking, contaminants and radioactive elements. By analysing suspended particulate matter from various ocean depths, various factors controlling the transfer of carbon from the surface to the deep ocean can be assessed.

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[26] See also *Nuclear and Isotopic Techniques for the Characterization of Submarine Groundwater Discharge in Coastal Zones* (IAEA-TECDOC-1595, 2008).

113. These sinking particles are the major vehicle for exporting carbon from the surface to the ocean floor. As these particles fall to the ocean floor, the organic carbon they contain becomes remineralized into inorganic form, which is much more easily released and redistributed into ocean waters at various depths. The extent of this redistribution determines how much CO_2 the ocean can absorb from the atmosphere. The natural radionuclide thorium-234 has increasingly been used over the past years to quantify particle fluxes and carbon export from the upper ocean in both open-ocean and coastal environments. Thorium-234 is a particle reactive isotope that is produced in seawater by radioactive decay of its dissolved conservative parent uranium-238. The disequilibrium between uranium-238 and the measured total thorium-234 activity reflects the net rate of particle export from the surface ocean on time scales of days to weeks.

114. The technique was recently applied in an international project in the coastal Arctic Sea for assessing the impact of permafrost melting due to climate warming, and the consequent increase in organic material outflow through rivers from the coast to open waters.

FIG. G-2. Deployment of an in-situ large volume pump to collect particulate material used to measure radionuclides in Arctic waters.

H. Water Resources

115. The third UN World Water Development Report[27] and the 5th World Water Forum, held in Istanbul in 2009, highlighted critical areas related to water in a changing world As a critical factor affecting human society and ecosystem sustainability, threats to water resources posed by climate change, rising food and energy costs, and the global economic crisis make addressing water problems all the more urgent.

[27] World Water Development Report 3 (UNESCO, 2009)
http://webworld.unesco.org/water/wwap/wwdr/wwdr3/index.shtml

116. Hence enhanced cooperation of agencies around the world is paramount to addressing the links between water and other factors. The Agency is addressing these links through its water resources programme. Isotope hydrology provides unique tools to address complex water problems, and helps managers and policy makers to understand the close link between energy and food production on the one hand, and water resource use on the other. Food and energy both have a major impact on the sustainability of water resources, and the availability of water will have a major impact on how well growing demands for food and energy will be satisfied. A multitude of factors affect and are affected by water resources or the lack thereof, and the links between water and political, economic, social, and environmental factors and pressures shown in Figure H-1 point to a need for integrated water resources management and integrated planning.

117. Far too often, a lack of understanding of hydrological systems and water cycling at the local and national levels hampers effective and sustainable management of water. Nuclear approaches, in the form of isotope hydrology, help to address this shortcoming, and may be a much faster way of obtaining key information than traditional hydrological monitoring approaches.

118. Isotope techniques for the assessment of water resources are becoming more accessible due to the expanded use of recently developed laser spectroscopy analyzers for measuring water isotopes. The IAEA played an essential role in assessing the performance of the technology and is now assisting Member States with procuring the analyzers as well as by providing training to technicians. These instruments are cheaper and easier to use than isotope ratio mass spectrometers which have been commonly used since the 1940s. Therefore this technology allows for an increasing number of water resources experts and groups to access isotope tools for the assessment of water resources. The use of this laser technology is expected to grow exponentially over the next decade.

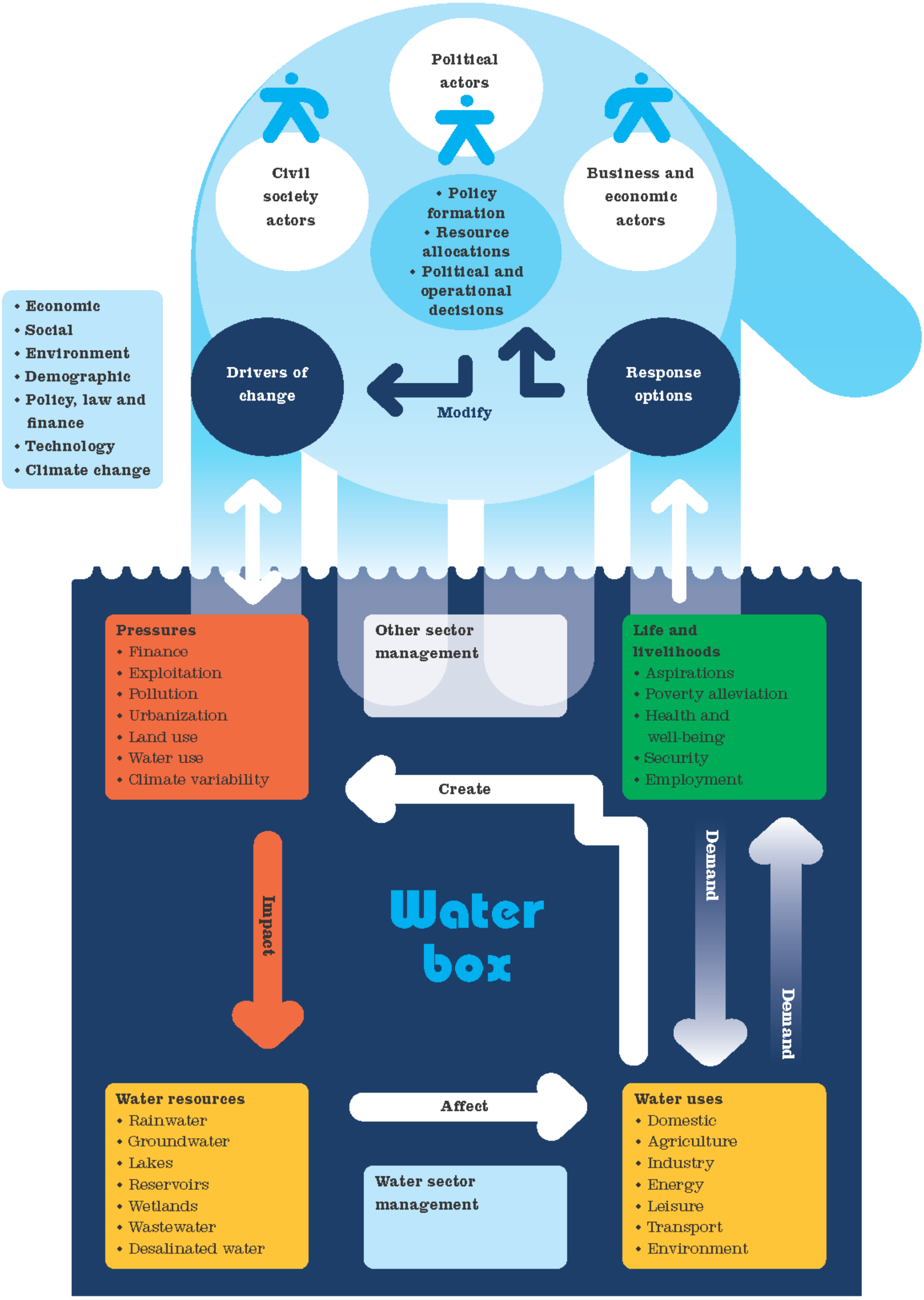

FIG. H-1. The social, political, and economic elements and processes that affect the sustainability of water resources (Source: UN World Water Development Report 3, 2009).

H.1. Fact before act

119. Among its key messages, the 5th World Water Forum emphasized the 'fact before act' idea through its theme "Bridging Divides for Water" (i.e. adequate understanding of how a particular hydrological system functions is required first, so that the right management actions can be taken later). To adapt to or mitigate the impacts of climate change, it is essential to first understand the status and functioning of a given water resource under current conditions. The 5th World Water Forum[28] issued three key recommendations that are relevant to the application of nuclear technologies:

- ✓ Better understanding of the impacts of global changes on water resources, natural hydrological processes and ecosystems;
- ✓ Development, implementation and strengthening of transnational, national and/or subnational plans and programmes to anticipate and address the possible impacts of global changes are required;
- ✓ Greater support for research in the field of water for sustainable use and management is needed and cooperation between international agencies should be promoted.

H.2. Using stable isotopes to understand groundwater availability and quality

120. Increasingly, stable isotopes approaches are used to understand the spatial distribution of various processes affecting groundwater availability and quality both at the local level and the global level. This approach is demonstrated in Figure H-2 where a map of groundwater oxygen-18 values from the Los Naranjos area of Mexico demonstrates the importance of high elevation recharge in the northwest part of the study area (blue colours) and impacts of lower elevation surface water infiltration in the rest of the area (red and orange colours). Such information provides a key baseline for assessing the impact of climate change and other factors on the local groundwater resources.

[28] See http://www.worldwaterforum5.org/

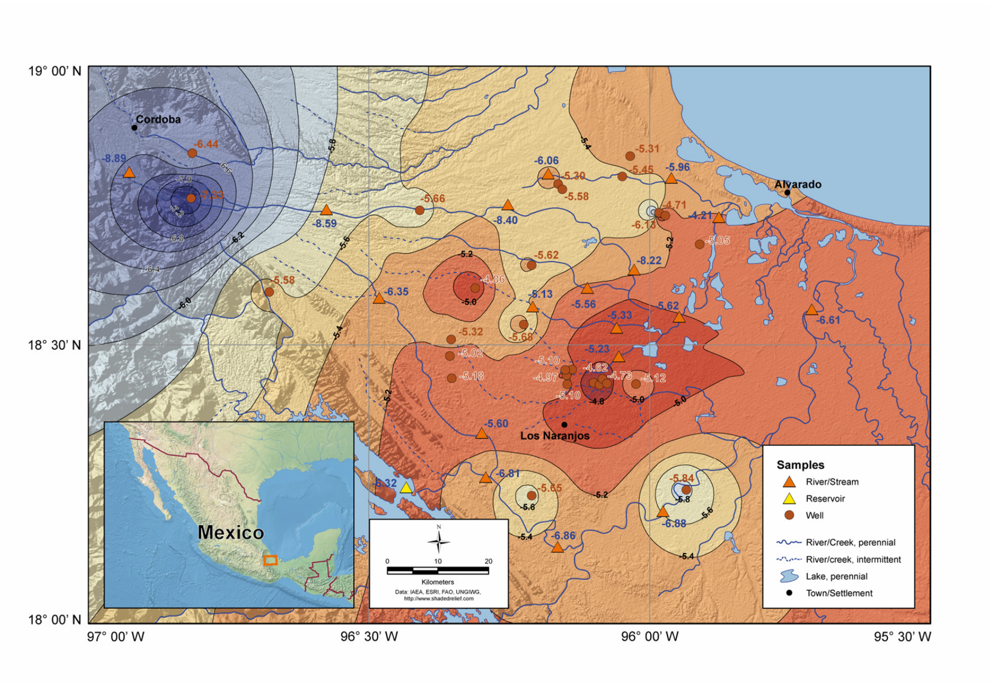

FIG. H-2. Interpolation of oxygen-18 groundwater values for the Los Naranjos area in Mexico. The more negative isotope values (blue colours in the upper left) indicate high elevation recharge. The red and orange colours indicate contributions of low elevation recharge and mixing.

121. As isotope hydrology helps to improve the assessment of water resources, it also has a role in energy planning. Together, staff of the Agency's water resources programme, the Soil and Water Management and Crop Nutrition Section of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, and the Planning and Economic Studies Section of the Department of Nuclear Energy are cooperating on an initiative related to climate, land, energy and water (CLEW) planning. If and when an approach is successfully developed, it would be used to assist Member States evaluate the combined impacts of a wide range of issues, including economic, social, environmental, demographic, policy, legal, financial, technological and climate change. CLEW planning also would facilitate cooperation between different government ministries and agencies to develop integrated solutions for sustainable water and energy development.

I. Radioisotope Production and Radiation Technology

I.1. Radioisotopes and radiopharmaceuticals

I.1.1. Radioisotope products and their availability

122. The ever increasing demand for radioisotopes for medical and industrial applications as well as advances in related technologies received worldwide attention in 2009 owing to the serious shortages faced in the supplies of medical isotopes, especially fission-produced molybdenum-99. Reactor-produced radioisotopes continue to be the mainstay for medical and industrial applications, while production capacities from cyclotrons also continue to rise, mainly due to the establishment of regional centres producing radioisotopes with very short half-lives for positron emission tomography

(PET). This and other recent advances in the development of radiopharmaceuticals were reflected in three major international meetings held in 2009.[29]

123. The increasing interest in the use of PET and PET/CT (computed tomography) is evident from the number of cyclotrons set up exclusively for the production of PET tracers. It is estimated that currently there are about 650 operational cyclotrons and 2200 PET systems throughout the world. Clinical use continues to be dominated by the well-established applications of fluorine-18 labelled fluorodeoxyglucose (FDG) in cancer patients, while there is also increasing focus on addressing the challenges and requirements for developing and using other PET radiopharmaceuticals. The improved availability of germanium-68–gallium-68 generators and the growing number of PET centres have boosted the development of gallium-68 based radiopharmaceuticals including related automated synthesis modules. The idea of using relatively longer lived PET radioisotopes for certain investigations of biological processes and distribution involving prolonged time periods has led to many centres exploring possible production of such PET tracers, for example copper-64 and iodine-124 products, using the spare operational time of existing medical cyclotrons. Another reason for the interest in these products is their role as accurate tools to provide dosimetric data for therapeutic applications that make use of analogous therapeutic radioisotopes.

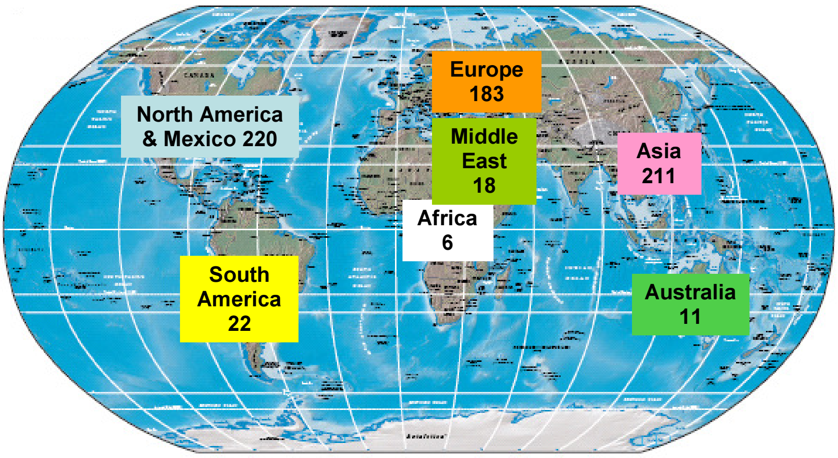

FIG. I-1. Distribution of cyclotrons for production of PET tracers
(source: Dr. D. Schlyer, Brookhaven National Laboratory, USA, based on inputs from four major cyclotron manufacturers)

124. The progress in radionuclide therapy approaches, for example, the treatment of neuroendorine tumours using lutetium-177 or yttrium-90 labelled peptides, has driven the development of automated synthesis units and shielding devices for small scale on-site preparation of therapeutic radiopharmaceuticals that requires the handling of relatively larger quantities of radioisotopes, as well as their PET-counterparts for dosimetry studies. Similarly, interest in using alpha emitting radioisotopes for therapy of cancer has led to further improvement of production methods of short lived alpha emitters, such as bismuth-213.

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[29] Annual Meeting of the Society of Nuclear Medicine in Toronto, Canada, and of the European Association of Nuclear Medicine in Barcelona; Spain; Biennial International Symposium on Radiopharmaceutical Sciences in Edmonton, Canada.

I.1.2. Security of supplies of molybdenum-99[30]

125. Severe shortages in the supplies of fission-produced molybdenum-99 and of technetium-99m generators have continued to affect medical diagnostic applications for patients in most parts of the world. The High Flux Reactor in Petten, Netherlands, has been shut down since February 2010 for required maintenance and upgrades and is expected to be restarted in August 2010. Furthermore, the National Research Universal reactor in Canada was shut down in May 2009 for major repairs due to leaks and is not expected to resume operation at least until late July 2010.

126. In order to partly compensate for shortages, production at the BR2 reactor in Mol, Belgium, and at the Safari-1 reactor in South Africa was increased to the extent possible. The Covidien isotope production facility in Petten, Netherlands, is utilizing the MARIA reactor in Poland to irradiate existing HEU targets for molybdenum-99 production to increase the molybdenum-99 supply. The production facility of the Institute for Radioelements in Fleurus, Belgium, is similarly utilizing the reactor in Řež, Czech Republic, for irradiating HEU targets. The Australian Nuclear Science and Technology Organisation (ANSTO) completed the hot commissioning of its new production facility that uses LEU targets irradiation in the Open Pool Australian Light Water (OPAL) Reactor and obtained regulatory approval to commence regular large-scale production, which will allow it to produce up to 10% of global demand for export. Another LEU-based production facility constructed in Egypt (based on Argentinian technology) adjacent to the ETRR-2 reactor has nearly completed the technical reviews required by the regulator and is scheduled to receive permission to begin hot commissioning by mid-2010.

127. Calls for international cooperation and for government support have come from various stakeholders, including professional medical bodies. At the request of the Government of Canada, the OECD/NEA formed the High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR)[31] to address relevant issues for enhancing the reliability of supplies of molybdenum-99.[32] Furthermore, the Association of Imaging Producers and Equipment Suppliers (AIPES) has intensified its role of coordination and dissemination of information related to reactor operational schedules and shutdown periods. In this regard, the Agency's support to facilitating research reactor coalitions has led to an entrepreneurial initiative involving four reactors in Central Asia and Europe and one processing facility in Hungary. The Canadian Government formed a four-member expert panel to recommend measures for securing radioisotope supplies for medical use and their report was released in December 2009[33].

I.2. Radiation technology applications

I.2.1. Electron beam sterilization of aseptic packaging materials and containers

128. Gamma radiation has been used as a safe and cost-effective method for the sterilization of disposable healthcare products, components and packaging for over 50 years. Electron beam (EB) radiation became accepted for sterilization about 30 years ago, when electron accelerators with improved efficiency and reliability became available and currently this is the method of choice for

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[30] Additional information is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2009/index.html) or at http://www.iaea.org/About/Policy/GC/GC54/Agenda/index.html).

[31] http://www.nea.fr/html/ndd/med-radio/

[32] The Agency is represented in the HLG-MR as an Observer.

[33] See http://nrcan.gc.ca/eneene/sources/uranuc/pdf/panrep-rapexp-eng.pdf

processing high volume/low value products (e.g. syringes) as well as low volume/high value ones (e.g. cardio-thoracic devices).

129. Recently, a new electron beam methodology, developed in the USA, became available, offering a chemical-free alternative for sterilizing or sanitizing aseptic packaging materials and containers. Aseptic packaging of fruit juices, dairy drinks, and other beverages is among the highest growth segments in the food processing industry and hence there is considerable interest in alternative package sterilization technologies that minimize energy and water consumption while delivering the required performance features. Currently 27 EB units of this type are installed or under construction throughout the world. The newest development in this area uses low energy EB emitters designed to sterilize the inside of beverage bottles (See Figure I-2). The EB emitters can be combined and configured in various ways and fitted in the production line enabling the sterilization of bottles, caps, bags and pouches. Depending on the configuration, either the inside or the outside, or both surfaces can be irradiated in a matter of seconds. In this way, high temperature treatment and the use of chemicals are eliminated as well as the rinsing after chemical treatment, thus saving both energy and water, lowering costs and simplifying logistics.

FIG. I.-2. Electron beam emitter sterilizing the inside of a bottle to be used for filling beverages (http://www.aeb.com/).

I.2.2. Radiation synthesis of carbon-based nanostructures

130. Carbon-based nanostructures, such as carbon nanotubes, have opened exciting possibilities in nanotechnology applications, especially the transformation from silicon-based microelectronics to nano-size. Electron beam based methods are uniquely suited to accomplish tasks such as welding of carbon nanotubes, patterning of structures containing carbon nanotubes by electron beam lithography, synthesizing metallic wires confined into nanotubes, and ion channelling for potential applications in drug delivery systems and the electronics industry. Last year, a group of researchers from Japan and China reported that by focusing a 120 keV electron beam on graphite nanoflake, it can be transformed to graphene, and further into a graphene nanoribbon. Continued irradiation finally leads to a single carbon strand which could be a perfect molecular wire. In this way, electron beam technology aids the manufacturing of most carbon-based nanostructures which have great potential as the ultimate basic components of molecular devices for medical and electronic use.

131. In order to facilitate the interaction between research groups, the transfer of scientific solutions to the industry and the products to the end-users[34], EUMINAfab, a consortium of European enterprises, universities and national laboratories in the area of micro- and nanofabrication, was established. It integrates technologies, installations and expertise and offers no fee access to 36 installations with the necessary technical support personnel in the areas of micro- and nanopatterning, thin film deposition, replication and characterization.

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[34] A similar scope was also covered by an Agency held in Romania on "Trends in Nanoscience: Theory, Experiment, Technology" that featured the role of radiation techniques in nanotechnology. This was organized jointly by the Abdus Salam International Centre for Theoretical Physics (ICTP), the IAEA and the Horia Hulubei National Institute of Physics and Nuclear Engineering.