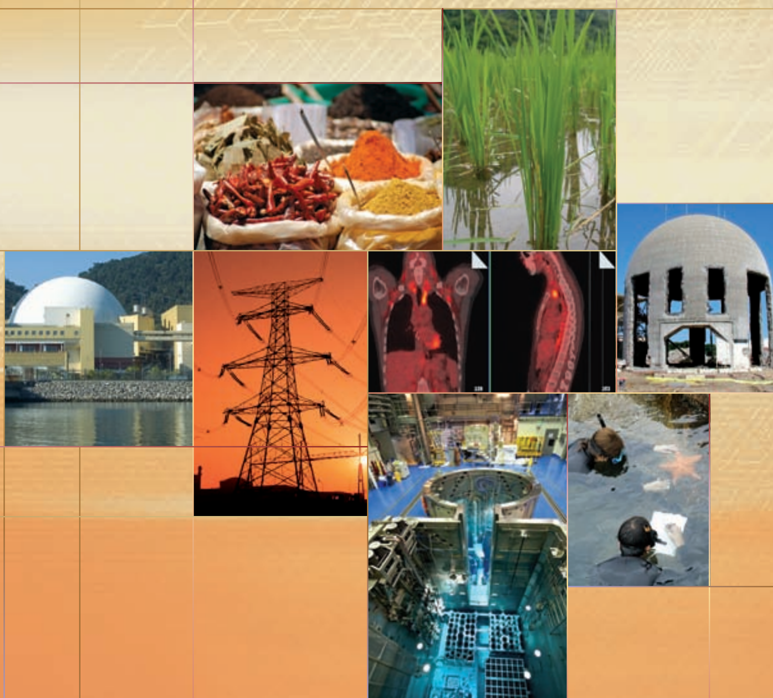
NUCLEAR TECHNOLOGY REVIEW

2010



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NUCLEAR TECHNOLOGY REVIEW 2010

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

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2010

Printed by the IAEA in Austria
September 2010
IAEA/NTR/2010

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CONTENTS

EXECUTIVE SUMMARY

In 2009, construction started on 12 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.

Current expansion, as well as near term and long term growth prospects, remain centred in Asia. Ten of the 12 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.

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

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

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.

The Board of Governors has authorized the IAEA 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 IAEA and the Russian Federation was signed in March 2010.

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.

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.

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 socioeconomic development in many countries throughout the world.

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.

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.

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.

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

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).

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.

There were 12 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.

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

Current expansion, as well as near term and long term growth prospects, remain centred in Asia. Of the 12 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.

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.

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.

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

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.

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 IAEA interest in considering the introduction of nuclear power. The number of IAEA technical cooperation projects on the introduction of nuclear power tripled in 2009. A brochure on a new IAEA 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 IAEA 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 IAEA 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				

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 1 JANUARY 2010)[a] (cont.)

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
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	1 900	78.0	48.6	368	6

TABLE A.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 1 JANUARY 2010)[a] (cont.)

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
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 IAEA's Power Reactor Information System (http://www.iaea.org/pris).

[b] 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 shut down 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

Each year the IAEA 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 371 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.

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.

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 IAEA 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.

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.

The IAEA'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.

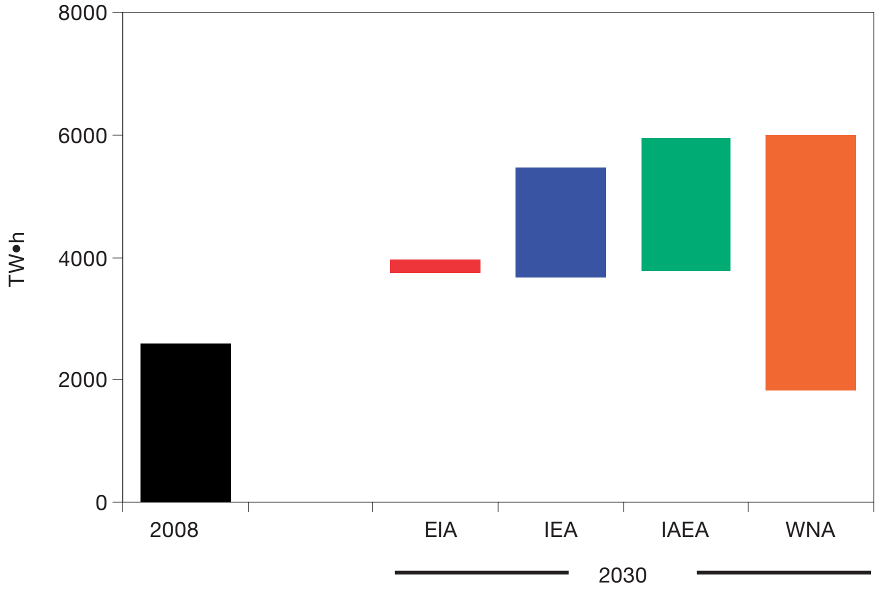

FIG. A.1. Comparison of nuclear power projections by the EIA, IEA, IAEA and WNA.

A.3. Fuel cycle[1]

A.3.1. Uranium resources and production[2]

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.

[1] 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.

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

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.

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 the USA, and with higher uranium prices recently there is renewed interest in this area in Australia, Brazil, France, India, Jordan, Morocco, Tunisia and USA. 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.

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.

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.

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 Fig. 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.

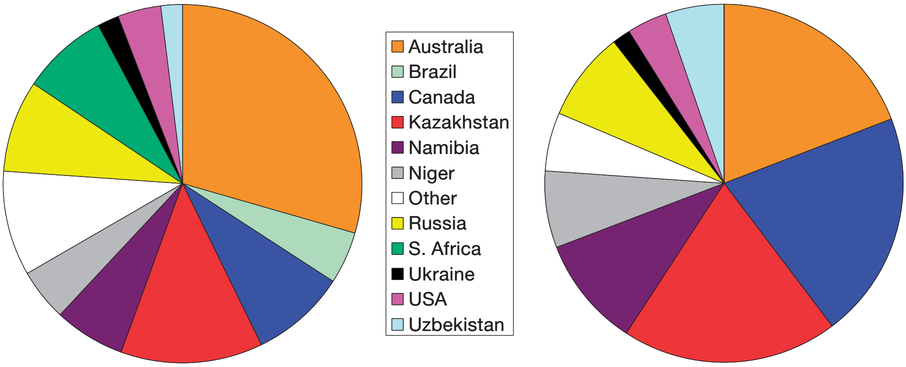

FIG. A.2. Geographical distribution of identified conventional uranium resources recoverable at less than $130/kg U (left) and of uranium production in 2008 (right).

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

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.

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.[3] 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.

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.

In November the Board of Governors authorized the IAEA'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 IAEA and the Russian Federation was signed in March 2010.

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

[3] 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.

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.

A.3.3. Back end of the fuel cycle

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.

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.

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.

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.

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

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

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 IAEA, grouped by region.[4]

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.

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

The Massachusetts Institute of Technology (MIT) updated a cost study for the USA that it had done in 2003[5] — its updated overnight cost estimate of \$4000/kW(e) is very close to the mean of the estimates for North America in Fig. 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

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[4] 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 green field 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.

[5] MASSACHUSETTS INSTITUTE OF TECHNOLOGY, The Future of Nuclear Power: An Interdisciplinary MIT Study, MIT, Cambridge (2003). Available at: http://web.mit.edu/nuclearpower/

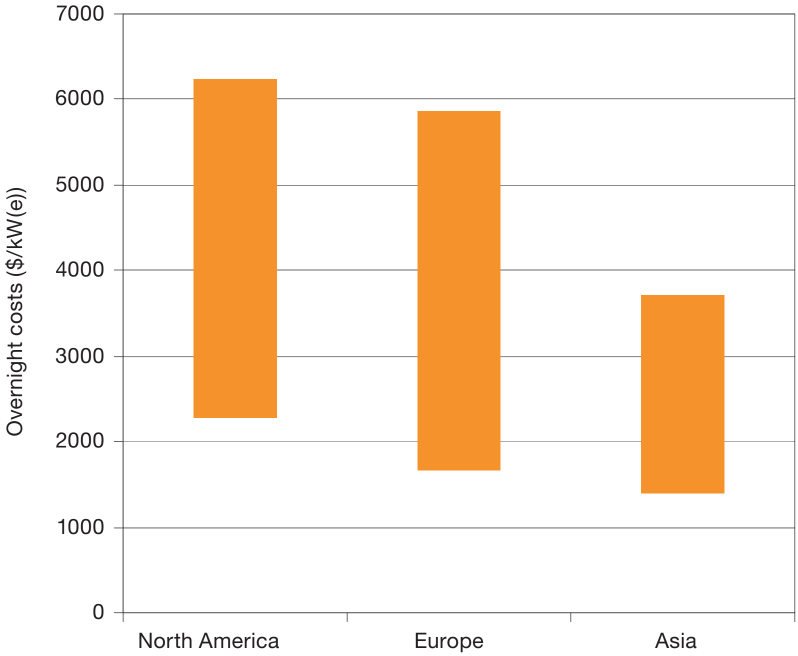

FIG. A.3. Ranges for overnight cost estimates by region, from 2007–2009 (2008 dollars).[6]

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.

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 Fig. 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

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

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.

A.4.2. Safety[7]

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.

More detailed safety information and recent developments related to all nuclear applications are presented in the IAEA's *Nuclear Safety Review for the Year 2009*.

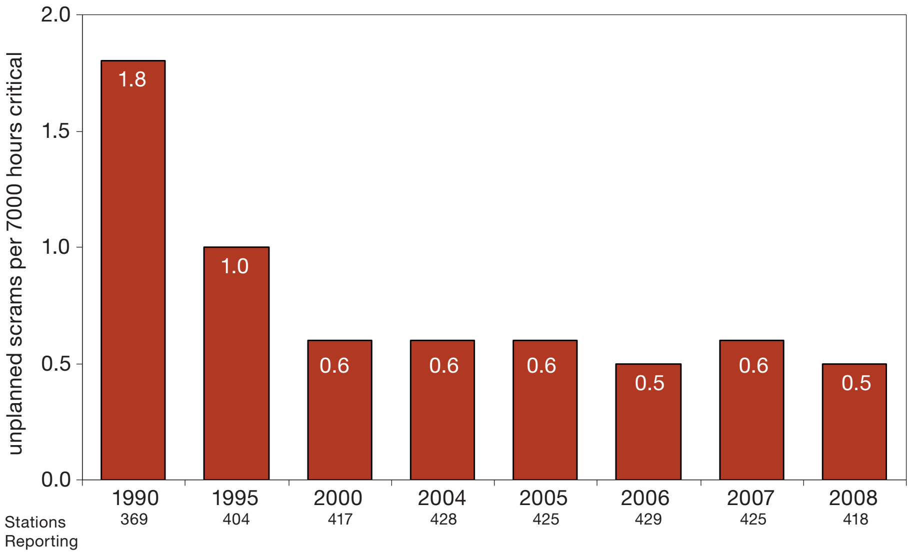

FIG. A.4. Unplanned scrams per 7000 hours critical (source: WANO 2008 Performance Indicators).

[7] More detailed information on IAEA activities concerning nuclear safety is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2009/index.html) and at http://www-ns.iaea.org/.

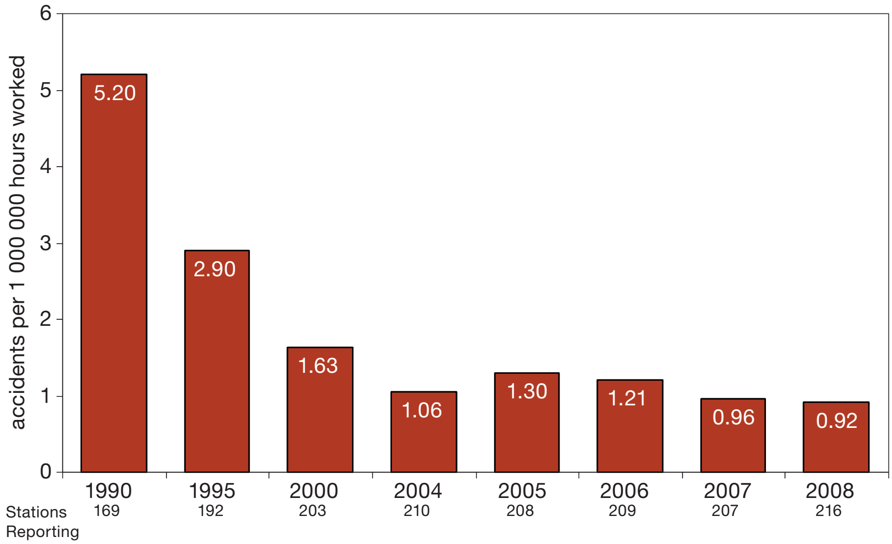

FIG. A.5. Industrial accidents at nuclear power plants per 1 000 000 person-hours worked (source: WANO 2008 Performance Indicators).

A.4.3. Human resource development

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.

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.

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 IAEA'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.

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;
— For estimating the investments and lead times necessary to expand existing education and training programmes to fill any projected workforce gaps.

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 IAEA, 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[8]

B.1.1. INPRO and GIF

The IAEA'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

[8] More detailed information on IAEA activities concerning advanced fission reactors is available in relevant sections of the IAEA Annual Report 2009 (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).

nuclear development; innovations in nuclear technology; innovations in institutional arrangements; and the INPRO dialogue forum on nuclear energy innovations.

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.

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.[9]

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

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

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

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

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

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 LWRs 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*[10] and will be described in more detail in the IAEA's forthcoming 2010 update of the *International Status and Prospects of Nuclear Power.*

B.2. Fusion

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.

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

Through their formal Cooperation Agreement[11], the IAEA 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 IAEA 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.

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

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 IAEA, 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 year for the last two years.

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

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

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.

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

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

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.

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

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 IAEA, 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.

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.

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 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.

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, the Libyan Arab Jamahiriya, 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.

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, Republic of Korea, 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.

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[12]

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[13]. Genomic and phenotypic data have been acquired from over 4000 sheep and goats of 89 breeds (see Fig. E.1). This data will be used to identify common genes that could be exploited for improving animal production.

Radiolabelled nucleotide probes have contributed to the sequencing of the full bovine genome[14]. 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

[12] 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).

[13] 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)

[14] The Bovine Genome Sequencing and Analysis Consortium, ELSIK, C.G., TELLAM, R.L., WORLEY, K.C., The Genome Sequence of Taurine Cattle: A Window to Ruminant Biology and Evolution Science **324** (24 April 2009) 522–528.

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.

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

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 IAEA has also been involved in the use of radionuclides for entomological research to address insect pest problems. The IAEA'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 IAEA 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.

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.

In 2009, the IAEA and 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 (Figs E.2 and E.3).

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.

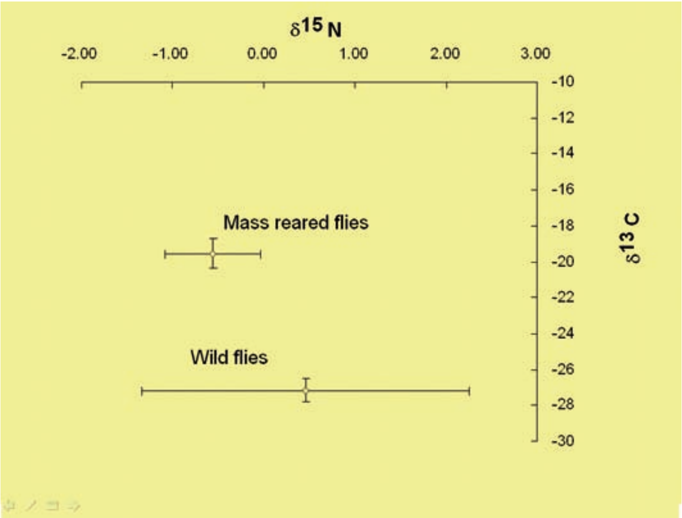

FIG. E.2. The signature of stable isotopes can be used to distinguish released mass-reared laboratory flies from wild flies for pest population monitoring purposes as part of the implementation of sterile insect technique programmes. This figure shows the mean isotopic signatures of male Ceratitis capitata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

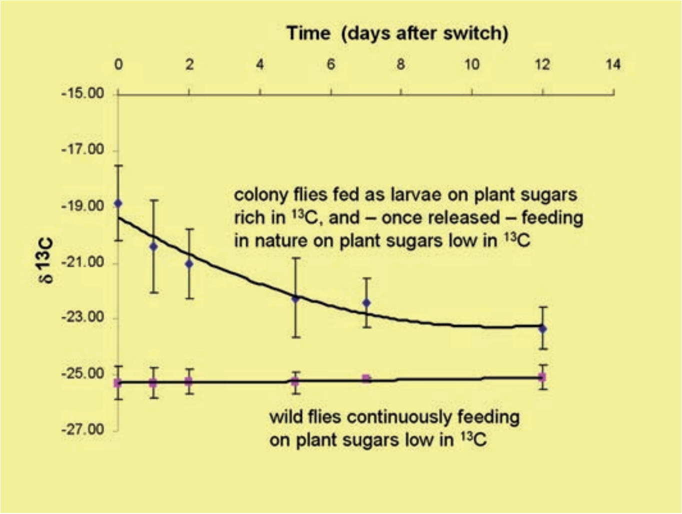

FIG. E.3. The isotopic signature of mass-reared flies persists throughout their lives, even when the flies are released on day 0 when they switch from a larval diet high in carbon-13 to an adult diet low in carbon-13 mimicking sterile insect technique practice. It is possible to distinguish sterile from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

E.3. Food quality and safety

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.

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 (Fig. E.4). 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.

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.

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.

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

E.4. Crop improvement

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[15]. 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.

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

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

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

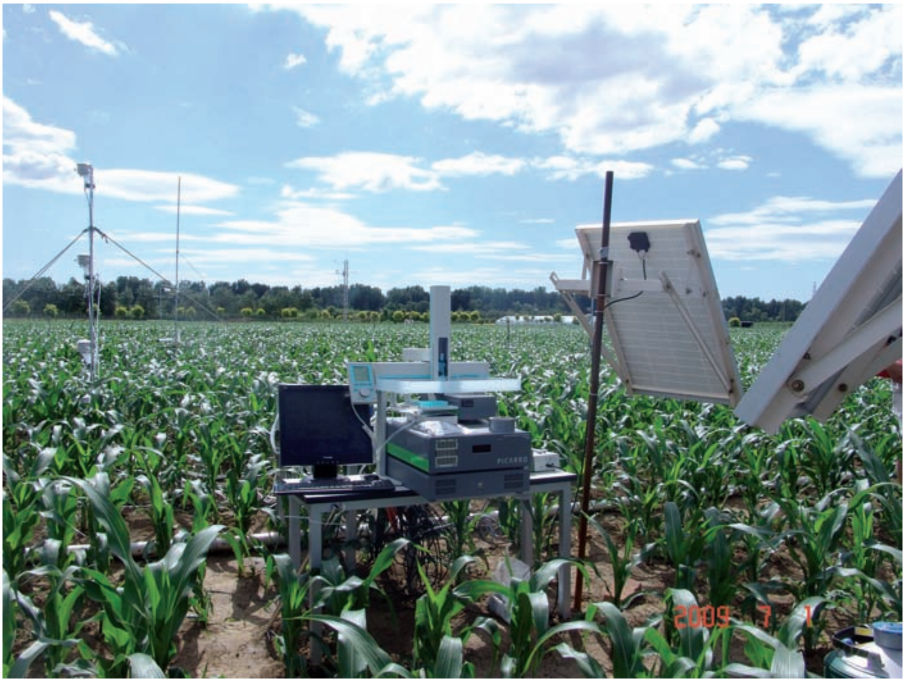

FIG. E.5. Measuring soil evaporation and plant transpiration from a maize field using conventional and isotopic techniques (courtesy of Xurong Mei).

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 (Fig. E.5). The information obtained will be used to develop technology packages and models to improve land and water management in different environments.

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

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[16, 17].

F. HUMAN HEALTH

F.1. Combating malnutrition with nuclear techniques

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 (see Fig. F.1). 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.

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.

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[16] See also TRUMBORE, S., *Radiocarbon and Soil Carbon Dynamics,* Annual Review of Earth and Planetary Sciences **37** (2009) 47–66.

[17] BRADFORD, M., FIERER, N., JACKSON, R., MADDOX, T., REYNOLDS, J., *Nonlinear Root-Derived Carbon Sequestration Across a Gradient of Nitrogen and Phosphorous Deposition in Experimental Mesocosms,* Global Change Biology **14** (2008) 1113–1124.

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 FAO[18].

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.[19] The IAEA 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.[20]

The importance of these efforts is highlighted in the recent Copenhagen Consensus 2008 report[21]. 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.

F.2. Hybrid imaging SPECT/CT and PET/CT[22]

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

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[18] WORLD HEALTH ORGANIZATION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Guidelines on Food Fortification with Micronutrients (ALLEN, L., DE BENOIST, B., DARY, O., HURRELL, R.F., eds), http://www.who.int/nutrition/publications/micronutrients/9241594012/en/index.html

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

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

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

[22] 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.1. Infants, children and women of child bearing age in developing countries are the most vulnerable population groups at risk of the 'hidden hunger' (photo courtesy of Stephanie Good, Ethiopia).

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.

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 (see Figs F.2 and F.3). 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.

F.3. Advances in radiation oncology applications

During 2009, several new technological developments emerged in the field of radiation oncology. These were highlighted in April 2009 during the IAEA's International Conference on Advances in Radiation Oncology (ICARO)[23].

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 IAEA, 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.

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.

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

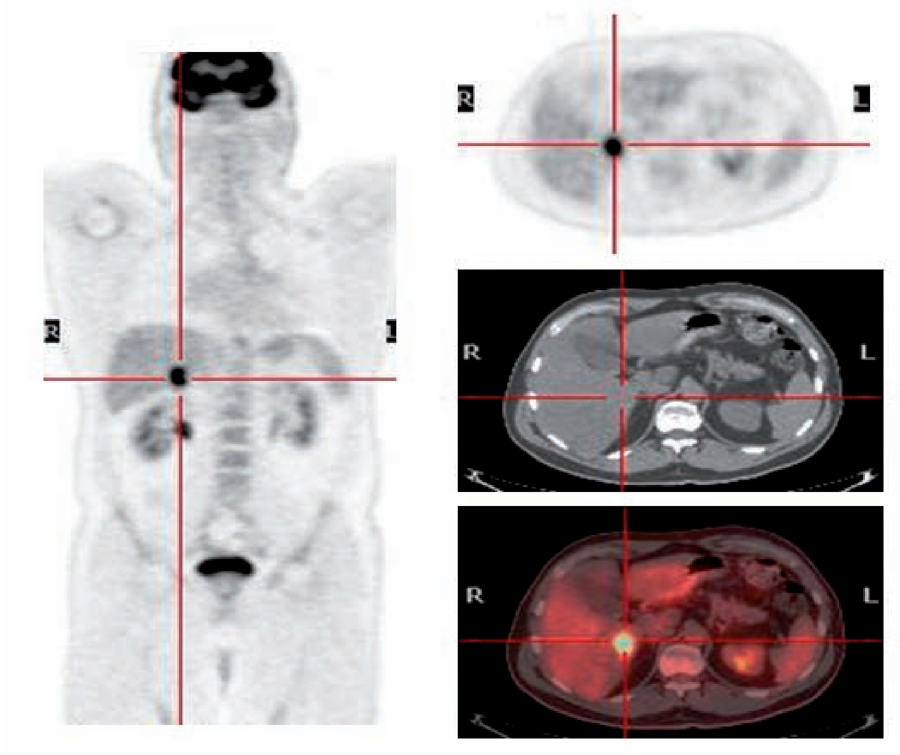

FIG. F.2. Images, such as the one above of the internal organs of a 50 year old man with a history of colonic cancer that has been surgically removed, are essential in monitoring the evolution of disease. The lighter areas show a rise in tumour marker due to possible tumour relapse. PET/CT shows single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

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.

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.

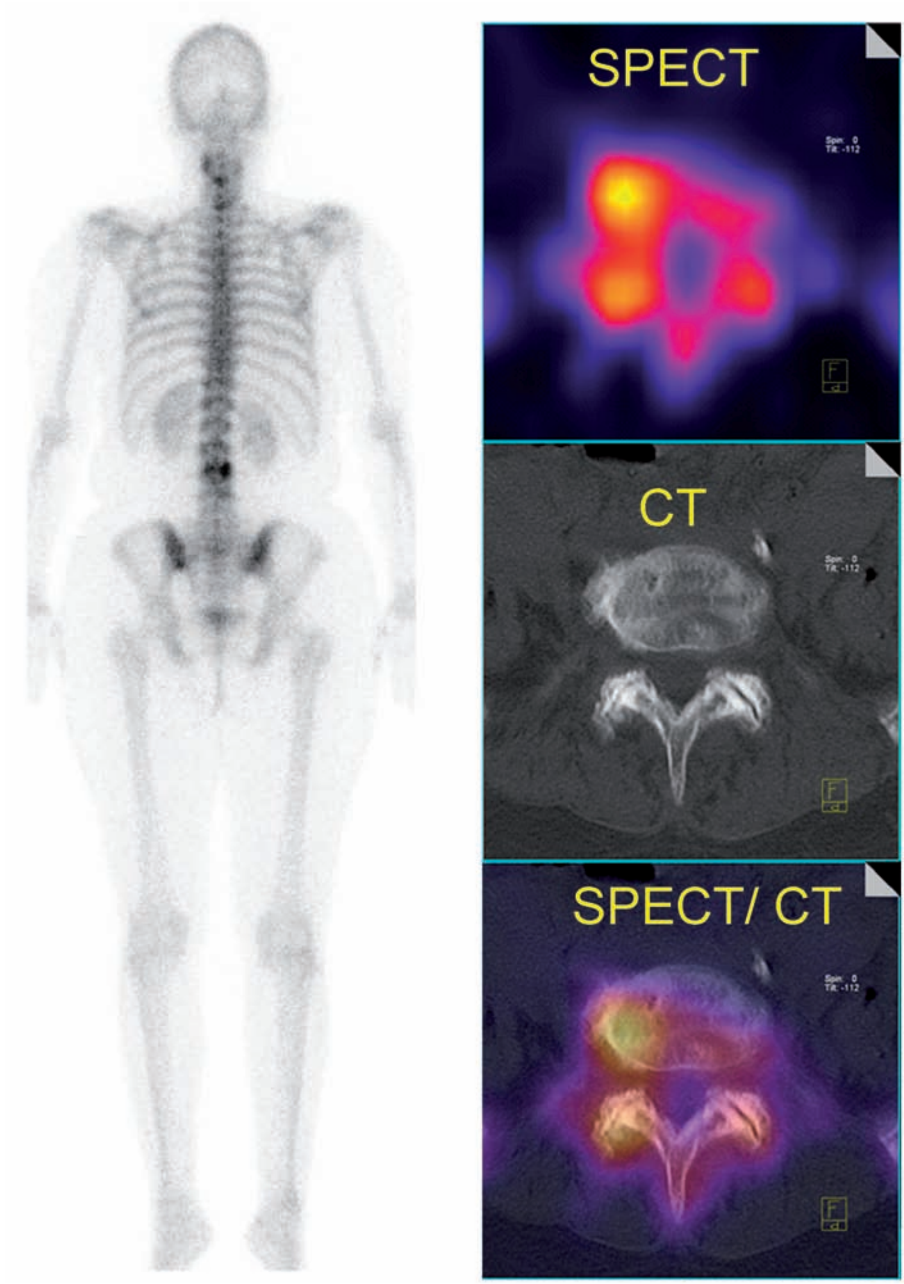

FIG. F.3. A SPECT study shows increased bone metabolism in the lumbar and cervical spine of this 65 year old woman with a previous history of melanoma. The co-registered SPECT and CT images show massive bone changes in the anatomy associated with degenerative processes. Bone metastases could be ruled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

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

Digital technology advances have facilitated an increase in the application of 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 F.4 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.

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 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.

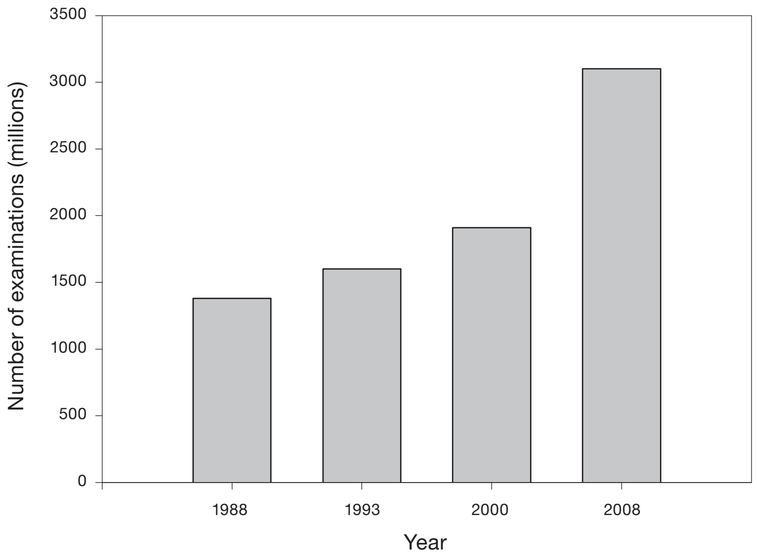

FIG. F.4. Worldwide trend in X ray radiological examinations (UNSCEAR official records, 2008).

G. ENVIRONMENT

G.1. Nuclear techniques for the quantification of submarine groundwater discharge[24]

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

[24] 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).

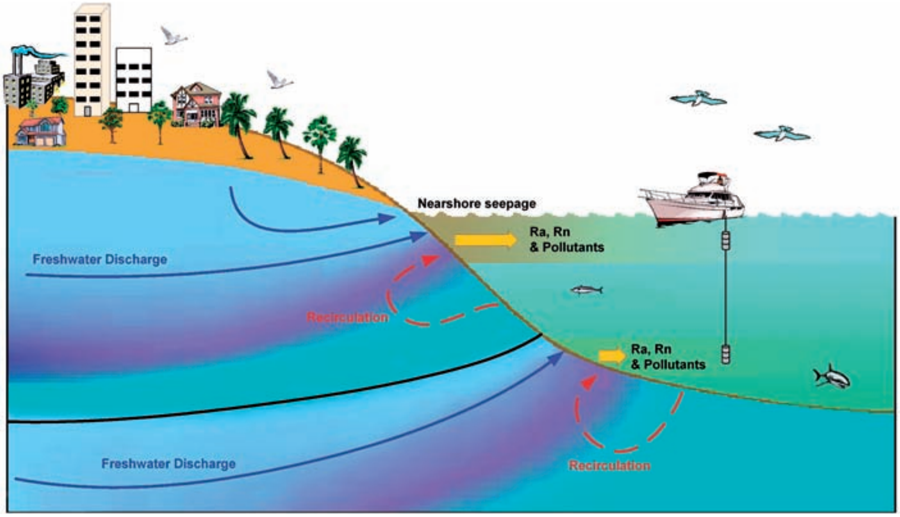

FIG. G.1. A depiction of the concept of submarine groundwater. The hydraulic gradient causes fresh water to discharge into the sea. Recirculation of seawater driven, for example, by tides contributes to SGD.

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, knowledge of the volume of submarine groundwater discharge helps to prevent overexploitation of coastal aquifers and prevent salt water intrusion (Fig. G.1).

Radium and radon measurement techniques have been developed to detect and quantify SGD in coastal regions;[25] 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

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

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

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.

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.

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).

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

The third UN World Water Development Report[26] 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.

Hence enhanced cooperation of agencies around the world is paramount to addressing the links between water and other factors. The IAEA 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

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

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 Fig. H.1 point to a need for integrated water resources management and integrated planning.

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.

Isotope techniques for the assessment of water resources are becoming more accessible due to the expanded use of recently developed laser spectroscopy analysers 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 analysers 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.

H.1. Fact before act

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[27] 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;

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

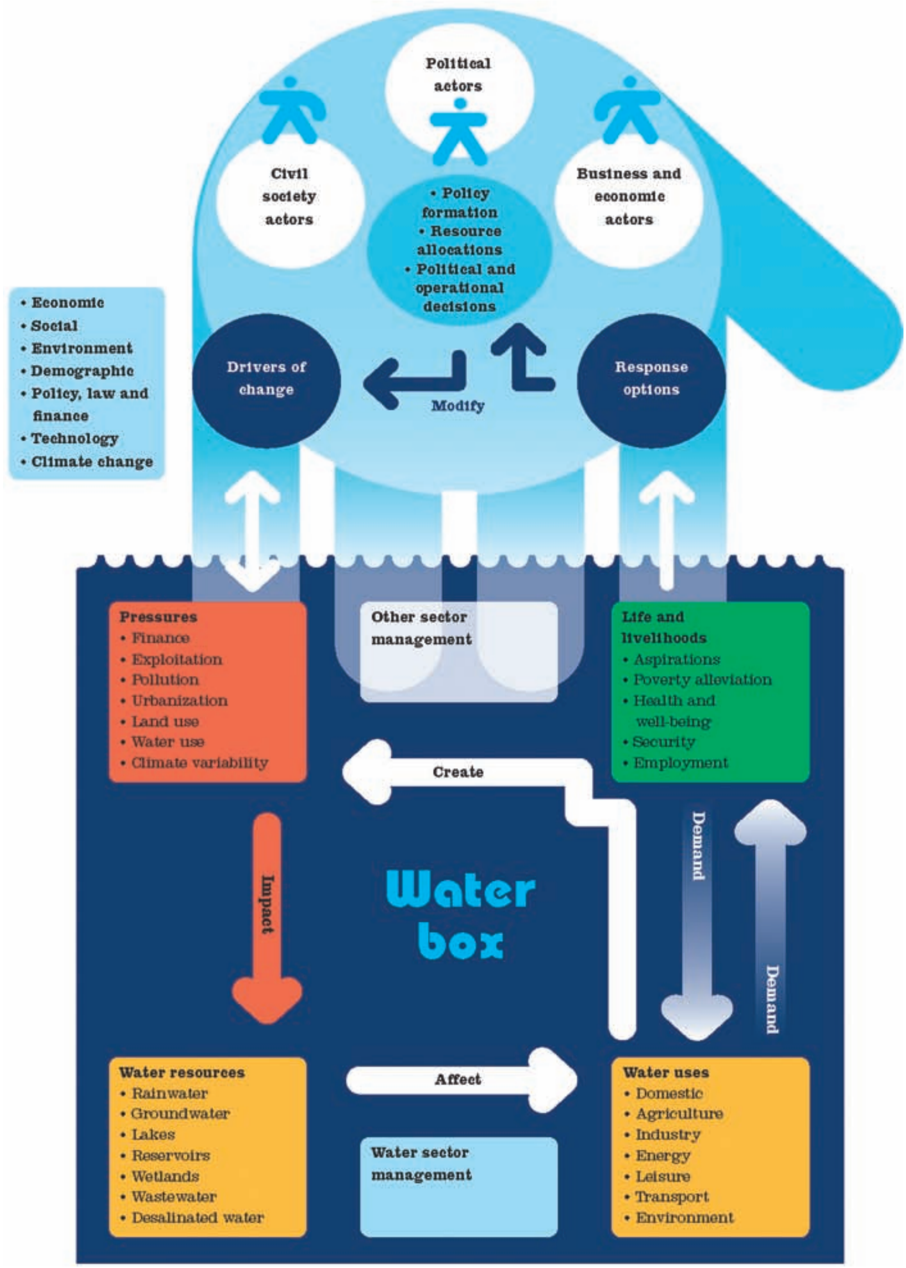

FIG. H.1. The social, political, and economic elements and processes that affect the sustainability of water resources (source: UN World Water Development Report 3, 2009).

— 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

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 Fig. 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.

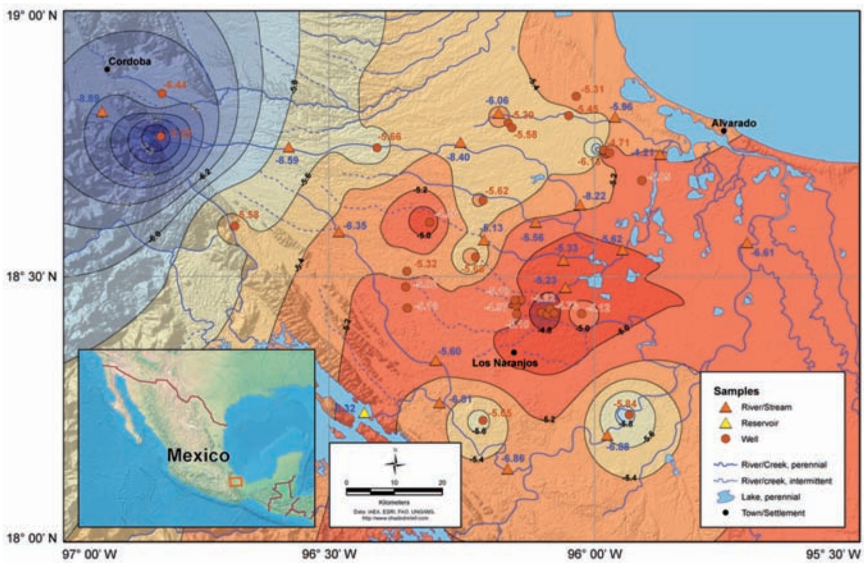

FIG. H.2. Interpolation of oxygen-18 groundwater values for the Los Naranjos area in Mexico. The more negative isotope values (blue colours in the upper left) indicate high elevation recharge. The red and orange colours indicate contributions of low elevation recharge and mixing.

As isotope hydrology helps to improve the assessment of water resources, it also has a role in energy planning. The IAEA is working 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

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.[28]

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 (Fig. I.1). Clinical use continues to be dominated by the well-established

[28] 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.

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.

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.

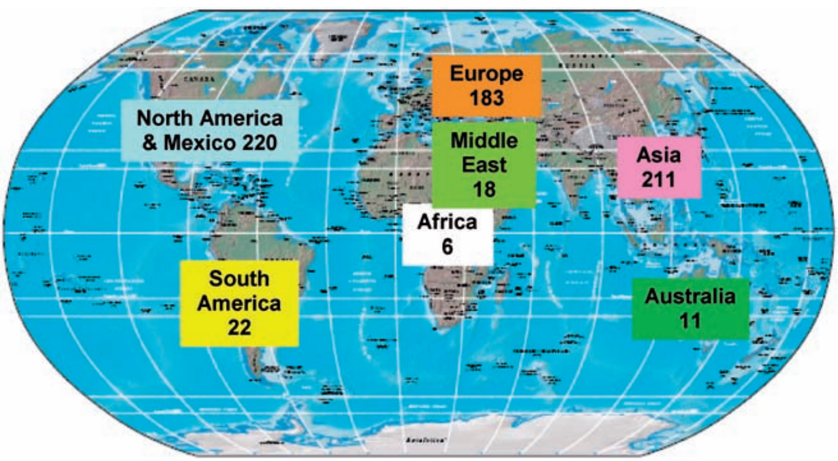

FIG. I.1. Distribution of cyclotrons for production of PET tracers (source: D. Schlyer, Brookhaven National Laboratory, USA, based on inputs from four major cyclotron manufacturers).

I.1.2. Security of supplies of molybdenum-99[29]

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.

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.

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)[30] to address relevant issues for enhancing the reliability of supplies of molybdenum-99.[31] 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

[29] 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).

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

[31] The IAEA is represented in the HLG-MR as an Observer.

IAEA'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[32].

I.2. Radiation technology applications

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

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

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 Fig. 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.

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

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

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.

In order to facilitate the interaction between research groups, the transfer of scientific solutions to the industry and the products to the end-users[33], 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.

[33] A similar scope was also covered by an IAEA meeting 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.

Annex I

RECENT DEVELOPMENTS IN NUCLEAR MEDICINE FOR CANCER MANAGEMENT: FROM NUCLEAR MEDICINE TO MOLECULAR IMAGING

I–1. Introduction to molecular imaging

The last decade has witnessed significant advances in medicine, particularly in the understanding of pathological processes at the molecular level, aided by the development — in parallel — of ever more sophisticated diagnostic imaging technologies. The increase of chronic diseases worldwide, including cancer, has spurred the development of a new biomedical research discipline, called Molecular Imaging, enabling the visualization, characterization, and quantification of biological processes taking place at the cellular and sub cellular levels. The images produced with molecular imaging reflect cellular and molecular pathways and mechanisms of disease present in the context of the living subject. Biological processes can be studied in their own physiologically authentic environment instead of by in vitro or ex vivo biopsy/cell culture laboratory techniques.

Also driven by the discipline of nuclear medicine — a branch of medicine that uses radioisotope labelled biologically active molecules called radiopharmaceuticals in the diagnosis and treatment of disease — these rapid developments in diagnostic methods and analysis have led to a paradigm change in the treatment of patients with cancer, from standard to personalized treatment. As a result of this change, the process of diagnosing and treating disease is shifting from a single specialist interacting with a patient to a multidisciplinary approach that retains a focus on the patient. Nuclear medicine faces a parallel evolutionary shift — from imaging function at the organ/tissue level to detecting changes at cellular and molecular levels. In this context, nuclear medicine is being coupled with other imaging modalities such as computed tomography (CT) or magnetic resonance imaging (MRI) to improve diagnostic accuracy and optimize patient care.

One of the most striking advancements of imaging technologies has been the introduction of positron emission tomography (PET), which has its foundations in the early 1930s, when Nobel Laureate Otto Warburg, a medical doctor and one of the twentieth century's leading biochemists, observed an increased use of glucose, a process called glycolysis, in rapidly growing tumours [I–1, I–2]. Fifty years later, some first experiments showed the increased incorporation in tumours of the glucose analogue fluoro-deoxyglucose (FDG) labeled with fluorine-18 [I–3] (^{18}F-FDG). This eventually led to the incorporation of in-vivo imaging of enhanced tumour glucose consumption using PET [I–4], for many types of cancers, involving all steps of cancer management, namely:

— Staging (assessment of the extent of disease prior to initiation of treatment);
— Response evaluation (assessment of treatment response during or after therapy);
— Restaging (assessment of the extent of disease following initial therapy or when recurrence has been confirmed);
— Detection of recurrence (assessment of the presence of cancer following clinical and/or biochemical suspicion of recurrence);
— Follow-up during or after cytostatic therapy (surveillance in the absence of clinical evidence of recurrence).

I–2. Medical imaging technologies and hybrid imaging

Imaging modalities such as CT and MRI will remain first line modalities in the investigation of cancers. However, when a PET study is used in the diagnosis of cancer patients it can cause changes in therapeutic decisions in 30–40% of the cases [I–5].

Diagnosis and characterization of disease by both CT and MRI imaging is based on morphological criteria such as size, texture and tissue attenuation. CT and MRI provide information regarding changes in organ size and tissue density, as well as their precise spatial localization and topographic landmarks. PET imaging, on the other hand, is based on the bio-distribution of a radioactive agent over time and space, enabling visualization of dynamic physiological and pathophysiological processes that define the functional characteristics of disease.

Due to inherent characteristics of nuclear medicine images and their limited resolution power, it is difficult to define the precise anatomical location of diseases, making the interpretation of studies a complex process. To overcome this limitation, the molecular and functional imaging provided by PET and the anatomical imaging provided by CT, have been merged into “hybrid imaging” using combined scanners such as PET/CT [I–6] while prototype PET/MRI scanners are already in development [I–7]. These hybrid modalities allow in a single diagnostic procedure a combined evaluation of function and structure, while obtaining the most from each modality. The introduction of hybrid imaging offers the possibility to re-examine the diagnostic process, the order in which studies are performed, as well as the construction of the therapeutic pathway (Fig. I–1).

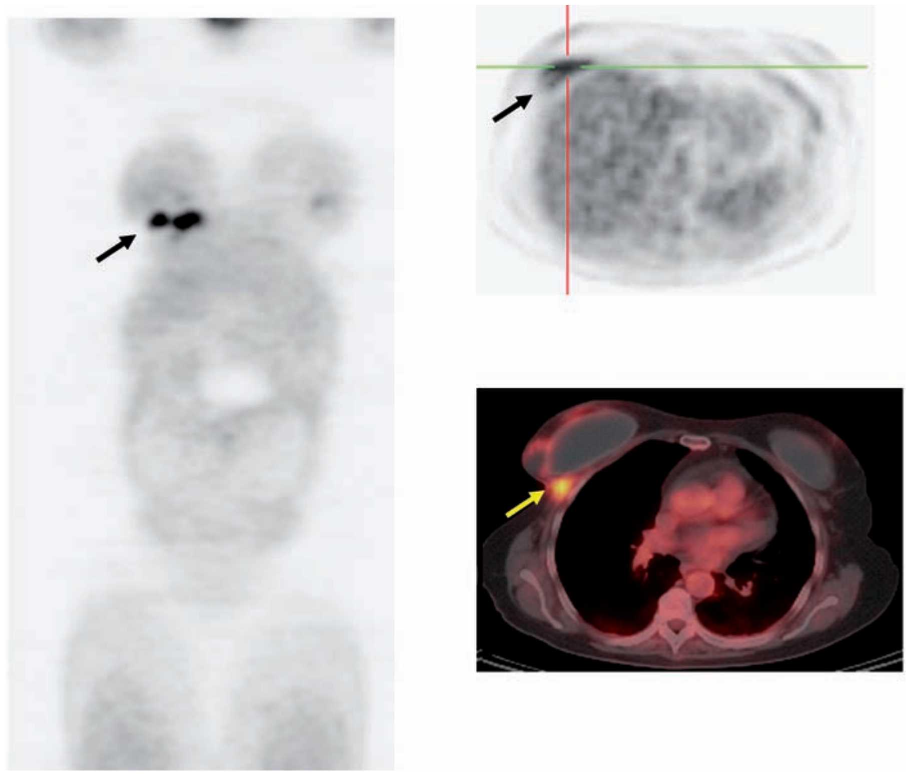

FIG. I–1. Female 52, with recurrence of breast cancer; PET shows an area of increased uptake in the right breast, lateral to the prosthesis. The CT cannot characterize the nature of the lesion. The combined PET/CT can locate recurrence and ensure that there is no bone extension thus changing the treatment option.

The technologies described below are key elements in the discipline of nuclear medicine.

I–2.1. PET/CT

PET produces a 3 dimensional picture of functioning processes in the human body, allowing for the evaluation of tissue metabolic activity. In PET a positron emission radionuclide — or tracer — able to track a specific biologic process at molecular level is injected into the patient. As these radioactive tracers decay, they emit positrons, which are then detected using a PET scanner. The resulting images will help distinguish between normal and abnormal cellular/molecular activity. Positron emitters are radionuclides like fluorine-18, carbon-11, oxygen-15 and nitrogen-13, which in their non-radioactive state are normal constituents of all biologically active molecules (fluorine is a suitable substitute for hydrogen) and are therefore potentially suitable to label any molecule without altering its metabolic pathway.

A simple way to describe the tumour growth process is that tumours need to divide, multiply and invade the neighbouring structures or tissues and spread to distant sites, a process called metastasis. To grow and metastasize, tumours require energy and the utilization of glucose — the fuel used by the body to produce energy — provides the necessary elements for this activity. While normal cells use glucose, there is an increased consumption of glucose within tumour cells.

Labelled with fluorine-18, a glucose analogue like FDG is used as a tracer, both because fluorine-18 is quick to decay, thus limiting patients' radiation exposure and because it is a natural indicator of cellular metabolic state, particularly increased in cancer cellular deposits and therefore easily detectable In diagnosing cancer with PET/CT, the most commonly used biologically active model is ^{18}F-FDG, a glucose analogue labelled with a radioactive element, the positron emitter fluorine-18, which allows the evaluation of glucose metabolism in normal and abnormal cells.

I–2.2. SPECT/CT

Another hybrid imaging technology, single photon emission computed tomography (SPECT), also allows visualization of functional information about a patient's specific organ or body system. Like in PET, a radiopharmaceutical or tracer is injected into the patient. Unlike PET, SPECT utilizes single photon emitters as tracers which does not require on-site dedicated cyclotrons for production. As this tracer decays, it emits gamma rays, which are then detected by a gamma camera. An essential tool in nuclear medicine, a sophisticated substitute for the X ray, the gamma camera can be used in planar imaging to acquire 2 dimensional images, or in SPECT imaging to acquire 3 dimensional images.

Coupled with CT, SPECT/CT has greatly improved neuroendocrine tumours diagnosis and staging using somatostatin receptor scintigraphy (SSRS) by improving detection sensitivity and localization of tumour foci [I–8]. The same is true for other tumour-seeking agents like meta-iodo-benzyl-guanidin (MIBG) and sestamibi labeled with single photon emitters such as indium-111, iodine-123 or technetium-99m. MIBG is a specific agent for neuroblastoma as well as of pheochromocytoma and other paragangliomas [I–9]. It still plays a major role in staging and follow-up of children with neuroblastoma, where it can also be used for radionuclide therapy [I–10].

As a general rule, scintigraphic images lack accurate anatomic landmarks for precise localization and characterization of findings, despite the fact that specific radiopharmaceuticals are used for assessment and diagnosis of specific disease processes. These considerations explain why morphological (CT) and functional imaging modalities (SPECT and PET) are complementary and not competing techniques, especially if precise image registration is made possible by using a single imaging unit combining the emission based data with the transmission based data (CT, which also serves to correct the emission data for tissue attenuation) (Fig. I–2). Called image co-registration, this process determines the geometric relationship between multimodality imaging studies, in order to use information provided by one test in the context of the other modality.

Simultaneous recording of CT and SPECT allows distinguishing tumour foci from normal tissue uptake such as in the gallbladder, kidney, spleen (including accessory spleens) and excretory pathways (urinary tract and intestines). It helps also to separate uptake due to activated lymphocytes and increased vascular permeability in inflammatory changes from tumours.

I–3. Role of PET/CT in cancer management

The introduction of FDG-PET (fluorodeoxyglucose-PET) has definitively changed the therapeutic approach to patients with non small lung cancer (NSCLC) [I–11] (Fig. I–3) and plays a major role in the initial evaluation of other tumours such as lymphomas [I–12], nasopharyngeal carcinomas [I–13], carcinomas of the uterus and cervix [I–14] (Fig. I–4), and gastrointestinal stromal tumours (GIST) [I–15].

FIG. I–2. Female 65 years old, with a neuroendocrine tumour (Pheochromocytoma). The SPECT–MIBG study shows an increased tracer uptake that is difficult to localize. The CT study shows no anatomical abnormalities. However, SPECT/CT allows one to localize the uptake in the left adrenal gland.

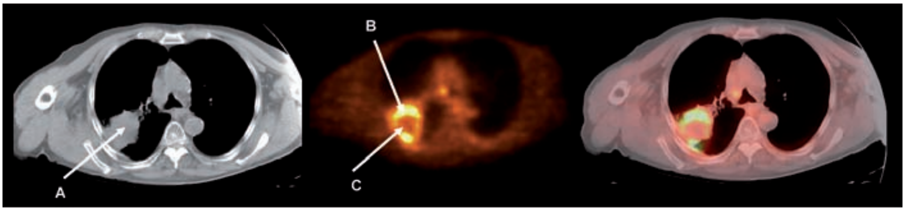

FIG. I–3. PET (central image) and CT images (left side image) of a patient with right lung carcinoma CT study shows an abnormal mass (A) that cannot be characterized. The PET study shows glucose uptake in the periphery of the lesion indicating the presence of viable tumour tissue (B) and no uptake in the centre, indicating central necrosis. (C) Combining PET/CT (right side image) is ideal for directing the biopsy to the active edge of the lesion.

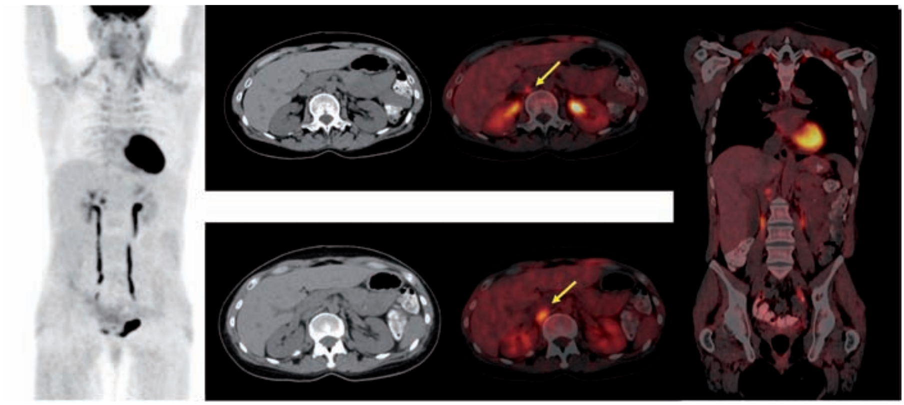

FIG. I–4. Female 43 years old, with ovarian cancer who had a PET/CT study to evaluate restaging post-treatment (surgery and chemotherapy). Two abnormal nodes consistent with metastatic disease were found in the lumbar region. The combination of PET and CT allows for a better localization of the disease.

It is also currently used for the detection of distant diseases in head and neck, colorectal, ovarian and small cell lung cancer as well as in locally advanced breast cancer and melanoma. Besides determining the stage, initial PET/CT can be used to assess the degree of FDG avidity of the tumours. It has been shown that in several tumour types the intensity of FDG uptake is correlated to the aggressiveness of the tumour [I–16]. In other tumours, such as lymphomas, particularly low-grade non-Hodgkin lymphomas (NHL) or GIST, it is important to evaluate the uptake intensity before treatment. In fact, some of these tumours are not FDG avid and consequently FDG-PET is not useful for evaluating treatment responses or detecting recurrence. In these cases it is important to use other radiotracers.[34]

There is evidence that complete disappearance of FDG uptake during the early course of treatment of lymphomas independent of the presence of residual tumours on CT is an excellent indicator of favourable prognosis [I–17]. Persistent FDG uptake, on the other hand, indicates poor response and, consequently, a high risk disease that might need more aggressive treatment. Similar observations have been made in other tumours, in particular NSCLC [I–18].

On the other hand, many oncologists tend to no longer administer complementary radiotherapy in young patients with complete metabolic response, as assessed by PET/CT, after chemotherapy of Hodgkin's disease, especially in female patients with mediastinal involvement, to avoid late second cancers. These medical practitioners adopt the principle of precaution, because — despite the great improvements of external beam radiation therapy in recent years — the incidence of unilateral or bilateral breast cancer is significantly increased in patients having previously been treated with radiotherapy for Hodgkin's lymphoma.

I–3.1. Assessing tumour response to therapy

Advances in the understanding of tumour biology have allowed for identifying targets involved in tumour proliferation, invasion and metastases that are addressed by newly developed drugs. These treatments are expensive and often have substantial toxic effects. It is therefore important to have tools to identify those patients who might benefit from treatment at an early stage. Tumour volume measurements using conventional tools like CT scanning sometimes may prove inaccurate because volume changes do not occur early enough. In some instances tumours might even grow initially in spite of responding to the treatment.

Nuclear medicine methods allow imaging and quantifying of the functional state of the tumour and therefore offer excellent surrogate markers of early response assessment [I–19]. Again, the most frequently used method today is FDG-PET. Several studies have shown a rapid decrease of FDG uptake in cancer cells after treatment with small molecule inhibitors of tyrosine kinase. A relationship between FDG uptake decrease and selective inhibition of oncogenes has also been shown.

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[34] For an earlier overview of advances in medical radiation imaging, see Annex IV of the Nuclear Technology Review 2006.

The first tumours in which the relationship between FDG accumulation and treatment response was used to guide therapy were GIST treated by the tyrosine kinase inhibitor imatinib, a drug with distinct target specificity. A dramatic decrease in FDG uptake was observed in these patients within the first days after the start of treatment. However, as soon as FDG uptake was no longer blocked, the treatment appeared no longer efficient necessitating either an adjustment of the dose or a change of the inhibitor.

This model has since been translated to other molecular therapies targeting specific processes at cellular/tissue level; in particular epidermal growth factor inhibition and inhibition of angiogenesis. These treatments have resulted in improved survival and symptom control of patients with NSCLC, but failed to improve outcomes when tested in large randomized trials. These results underline the importance of possessing a tool that allows for appropriately selecting the right patients for a therapy that is cytostatic rather than 'tumouricidal'. This is especially true because many cancers today are considered chronic progressive diseases that need continuous cytostatic treatment. It is crucial to have methods for following these patients in order to know if they still respond to the drug, especially since these drugs need to be administered in the optimal biological dose in order to keep the balance between efficacy and side effects, usually late in development and often irreversible. In addition, due to the high costs of these new therapies, they need to be restricted to patients most likely to benefit from them. FDG-PET is the first and most widely distributed of these surrogate markers of tumour response (Fig. I–5).

Other compounds are either in development or undergoing clinical testing. These include markers of cellular proliferation (^{18}F fluorothymidine), amino acid transport (^{18}F-fluoroethyltyrosine) or angiogenesis, i.e. production of new vascular tissue to ensure blood supply to the tumour. Such markers may ultimately not only serve to monitor targeted tumour therapy but also to assess target expression and heterogeneity, in order to select the most appropriate treatment for the individual patient.

Fluorine-18 labelled radiopharmaceuticals and radiolabeled peptides [I–20] also play an important role in the management of patients with neuroendocrine tumours. These peptides mostly target somatostatin receptors over expressed by these tumours. They may be labelled with single photon emitting nuclides such as indium-111 or the positron emitter gallium-68. This radionuclide is particularly interesting because it is a generator product and therefore available when needed even in centres not equipped with a cyclotron. PET images obtained with such gallium-68 labelled peptides are normally of superior quality because of the very low background in normal tissues (except kidneys and spleen), that allows the revealing of subcentimetric lesions as long as the receptor density is elevated [I–21].

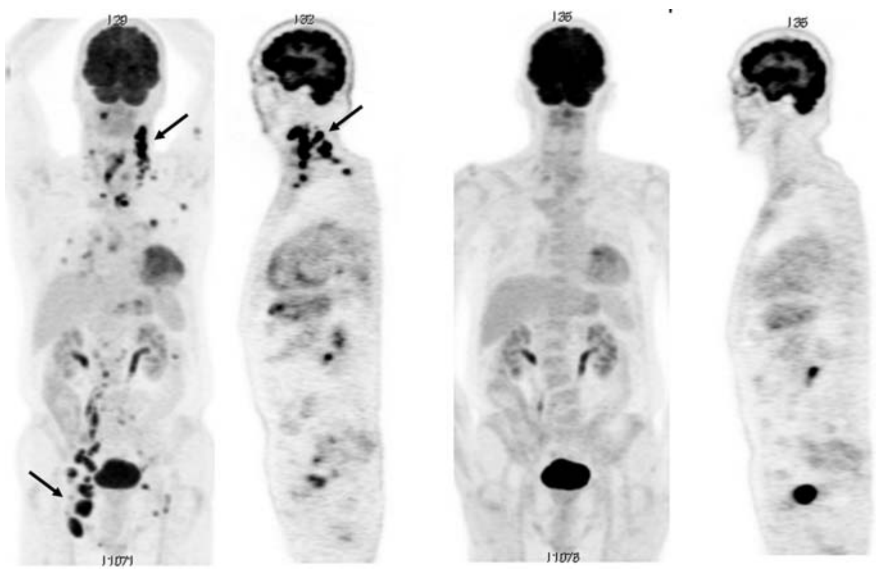

FIG. I–5. Male 40, with lymphoma. PET images pre-treatment show multiple sites of cancer diffusion (arrows). Images post-chemotherapy show a complete response to the therapy.

I–3.2. Radioguided minimally invasive surgery using SPECT/CT

The increase in the detection of occult lesions has led to the development of new localization methods using radiopharmaceutical products. The use of these products can be used to perform a 'thrifty' (less aggressive) surgical excision and, to simultaneously carry out the biopsy of the sentinel node in cases, for example, of breast cancer. Many studies clearly show the advantages of the radioguided surgery method, i.e. its effectiveness and attractiveness to surgeons. The sentinel node technique as well as the improved localization on fused SPECT-CT imaging [I–22] has stimulated the interest of surgeons in radioguided surgery beyond sentinel node dissection. SPECT-CT has proven to be very helpful in precisely identifying sentinel nodes especially in malignant melanoma of the trunk and head and neck area where drainage is much less predictable than in the breast area or in melanoma of the limbs. Somatostatin analog uptake may be localized intraoperatively in non-enlarged lymph nodes as well as in the pancreas where no definite nodular structure had been identified preoperatively. It is routinely used in many centers for minimal invasive resection of parathyroid adenomas. It may also be very helpful in identifying residual tumour bearing neck nodes after a previous neck dissection for thyroid carcinoma. Looking to the future, nuclear medicine is now beginning to experiment with radioguided minimally invasive surgery and PET probes are currently being developed, besides gamma probes, to take advantage of the high contrast of PET radiopharmaceuticals [I–23].

I–4. Targeted radionuclide therapy

Radionuclide therapy is the treatment of diseases by intracavitary, intravenous, oral, or other routes of administration of sealed and unsealed radiopharmaceuticals and is characterized by the selective delivery of radiation doses to target tissues and by limited toxicity and few long-term effects. The treatment may be systemic or applied loco-regionally. In the first case, it combines the advantage of being selective like external beam radiotherapy or brachytherapy with that of being systemic like chemotherapy. The basis of successful radionuclide therapy is a good and selective concentration and prolonged retention of the radiopharmaceutical at the tumour site.

Nuclear medicine offers the unique possibility to study distribution, uptake and biokinetics of trace amounts of the compound labeled with a single photon or positron emitter before using it for therapy after labeling with a beta emitter. Dosimetry has made great progress recently with the widespread availability of SPECT coupled or not to CT (SPECT-CT) that allows one to precisely compute three-dimensional radionuclide distribution over time, as well as volume measurements of tumours and normal organs [I–24].

I–4.1. Bone pain palliation in metastatic cancers using radiopharmaceuticals

Radionuclide bone therapy refers to the treatment of bone metastases using specific tumour seeking radiopharmaceuticals. Unlike radionuclide tumour therapy, where the radiopharmaceutical is incorporated into or fixed to the tumour cell, this form of bone therapy targets the reactive osteoblastic reaction in the normal bone directly adjacent to the metastasis, which is generally the cause of pain [I–25]. Bone therapy can also include the treatment of primary bone tumours, e.g. osteosarcoma, where the bone-seeking radiopharmaceutical behaves like a tumour seeking agent, targeting the tumour-produced osteoid of not only the primary tumour and its skeletal metastases, but also the extra-osseous metastases. Finally, it should be mentioned that palliative therapy of painful bone metastases with samarium-153 lexidronam [I–26] or strontium-89 chloride [I–27] offers complete or partial pain relief to a majority of patients with diffuse bone metastases, in particular from prostate cancer, and can substantially improve the quality of life of these patients.

I–4.2. Radiolabelled peptides

Radiolabelled peptides are not only used for diagnosis, staging and follow-up but also for the treatment of patients with neuroendocrine tumours. Labelled with yttrium-90 or lutetium-177, somatostatin analogues have been widely used for targeted radiotherapy [I–28]. Even if these tumours are not very radiosensitive, remarkable therapeutic effects have been obtained. While complete responses are only rarely observed, most patients experience stabilization of their disease, often for prolonged time periods, as well as disappearance/improvement of neuroendocrine symptoms. These treatments are well tolerated and can be repeated several times, though the dose to the kidneys, as the critical organ, must be closely monitored to avoid delayed kidney failure.

The example of somatostatin analogues in neuroendocrine tumours is in line with the long experience of nuclear medicine in imaging and the efficient treatment of benign and malignant thyroid disorders. Other therapeutic applications include the treatment of NHL with iodine-131 or yttrium-90 labelled monoclonal antibodies directed against the CD20 or CD22 antigens of B-cells [I–29]. A single administration of the yttrium -90 labelled ibritumomab tiuxetan in a consolidation setting after first-line therapy of follicular NHL has shown a high conversation rate of partial to complete, including molecular, response and an approximately two years prolonged progression free survival in comparison with the corresponding group of controls.

I–4.3. Radionuclide therapy with alpha emitters

Another approach is to target isolated tumour cells and preangiogenic micrometastases with monoclonal antibodies labeled with alpha emitters such as bismuth-213 or astatine-211 [I–30]. Targeted high LET (linear energy transfer) alpha emitting antibodies offer significant potential advantages in the treatment of diffuse micrometastatic or small volume disease. The interest in alpha emitters is predicated on the extreme high radiotoxicity of alpha particles. For example, it requires only 1–5 alpha particle passages through a cell nucleus to inactivate a tumour cell in contrast to several thousand for the same level of cell kill using a beta source. This is extremely attractive when working with isolated cells, or micrometastases where the amount of targeting may be extremely small, or when using antibodies e.g. M195, for which there is only a limited number (5×10^4) of antigens per cell. Further, the very short range of alpha particles (<90 μm) means that a larger portion of the radiation energy will be deposited in the tumour cells, effectively sparing normal tissues. Promising results have been obtained in leukemia or in bone marrow ablation [I–31] or, after intraperitoneal administration, in ovarian carcinoma [I–32], but most of these therapies are still experimental and need further confirmation and research.

I–4.4. Radiotherapy planning

More recently, a new potential use of PET/CT has been suggested and evaluated, namely its use as an aid to the treatment of cancers using external radiation beams [I–33]. Indeed, during radiotherapy planning FDG-PET/CT has been shown to be useful to better delineate the biologically active tumour volume (Fig. I–6) and to distinguish between viable tumour tissue and non-specific changes due to previous surgical and/or radiotherapeutic treatments.

To study brain tumours [I–34], FDG is most often replaced by either carbon-11 or flourine-18 labelled amino acids, as FDG is normally concentrated in the normal brain and therefore is less adequate for distinguishing tumour tissue from normal structures. PET also serves to demonstrate the poorly perfused, partially necrotic central parts of the tumour that might need an additional boost as hypoxia is known to decrease the efficacy of radiation. Several publications address the question of imaging hypoxia [I–35] before and during external beam radiotherapy to adapt the dose to the changing conditions. These are interesting approaches that are also attempting to tailor the treatment to the individual patient's needs in order to improve tumour control, while diminishing toxicity to normal surrounding structures and acute and late side effects. However, long term

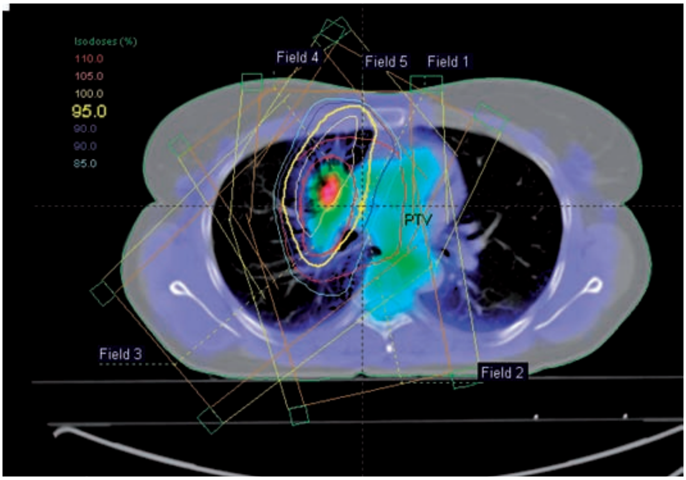

FIG. I–6. Planning for radiotherapy fields based on images from PET/CT in a patient with advanced stage lung carcinoma.

results are not yet available to definitively evaluate the outcome i.e. the therapeutic efficiency or toxicity of these approaches.

I–5. Conclusion

The key utilization of molecular imaging is in the interrogation of biological processes in the cells of a living subject in order to report on and reveal molecular abnormalities that form the basis of disease. This is in stark contrast to the classical form of diagnostic imaging where documented findings show the end effects of these molecular alterations typically via macroscopic and well established gross pathology. Molecular imaging includes the field of nuclear medicine along with various other fields that together offer an array of different strategies to produce imaging signals. Whereas nuclear medicine uses radiolabelled molecules (tracers) that produce signals by means of radioactive decay only, molecular imaging uses these as well as other molecules to image via means of sound (ultrasound), magnetism (MRI), or light (optical techniques of bioluminescence and fluorescence) as well as other emerging techniques.

Molecular imaging with radiolabeled tracers along with PET/CT and SPECT/CT currently plays a pivotal role in the management of patients with cancer. It assists in choosing the most appropriate therapy by refined staging, it evaluates the response to both chemotherapy, be it cytotoxic or cytostatic, and radiotherapy, and finally it contributes to the early detection of recurrence.

Furthermore, molecular imaging with PET/CT and SPECT/CT will strengthen personalized medicine by better characterizing the extent, the biological features and the response of the tumours. Intra-operative probes assist minimal invasive surgery for the removal of sentinel nodes and tumourinvolved structures, which may present unremarkable morphological changes. In addition, it offers efficient treatment by targeted radiotherapy of thyroid diseases, neuroendocrine tumours and non-Hodgkin's lymphoma as well as pain palliation in patients with diffuse bone metastases. New approaches with alpha particles are also under investigation. Finally, the use of PET-CT for the definition of biological tumour volumes and 'dose painting' in radiotherapy planning holds promise for less toxic but more efficient tumour control, although long-term confirmation is still required.

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Annex II

REDUCING THE RISK OF TRANSBOUNDARY ANIMAL DISEASES THROUGH NUCLEAR TECHNOLOGIES

II–1. Introduction

The challenge of ensuring food security for a world population that will grow to over eight billion people in the next 20 years can be met, in part, by assisting smallholder farmers in developing countries to improve the utilization of locally available land, water, and plant resources to intensify and increase animal production and productivity. This will require not only more sustainable livestock production, but also more efficient approaches, tools, and strategies for preventing, diagnosing and controlling animal diseases. The amount of available animal protein for human consumption is already limited, but the fragile food security situation is further exacerbated by increased movement of animals and animal products due to expanding world trade and the growing effects of climate change that can result in changes in the geographical distribution of pathogens and their vectors. Resource poor developing countries will become increasingly vulnerable to emergencies caused by the growing prevalence of infectious diseases, especially transboundary animal diseases (TADs). A complicating factor is that more than 60% of the TADs are zoonotic diseases (i.e. diseases of animal origin that infect humans), such as Human Immunodefficiency Virus (HIV), H5N1 (Avian Influenza) and H1N1 (Swine Flu), Rabies, Rift Valley Fever, and Trypanosomosis.

Classical or traditional techniques for diagnosing threatening diseases are well in place, but often lack the sensitivity and specificity needed to make accurate and timely diagnoses of diseases. Nuclear and nuclear related technologies have these features and are therefore increasingly being used to complement traditional diagnostic and tracing technologies to improve the early and rapid diagnosis and control of animal diseases through tracing and vaccination strategies [II–1]. The IAEA, through the development and application of nuclear and nuclear related technologies, is at the forefront of developing and validating early and rapid diagnostic techniques that are simple to use, inexpensive and can be applied in a 'laboratory limited' environment, such as those located in rural and decentralized areas; in the tracing of diseases through the application of stable isotope techniques; and in the application of irradiation technologies to provide safe and user friendly vaccines.

The application of nuclear technologies, in combination with conventional technologies, has contributed to concrete improvements in the number, condition and health of animals resulting in improved livelihoods for millions of people worldwide. For example, it is estimated that the eradication of rinderpest saves Africa more than US $1 billion per year (FAO). The unique characteristics of nuclear technologies not only contribute to our efforts to reduce transboundary animal disease risks, but also to the tracing and monitoring of animal movements (e.g. the tracing of disease infected migratory birds), as well as to the timely and proactive control and prevention of diseases through the use of vaccines.

II–2. Nuclear and nuclear related techniques for disease diagnosis

Nuclear applications have driven modern biotechnological research by providing more sensitive, specific and cost effective diagnostic platforms or assays to detect and characterize the disease pathogens [II–1]. Many of these nuclear based applications are being used in Member States for diagnosis of TADs such as rinderpest and rabies. The use of nuclear technologies allows the detection and characterization of pathogens within 24 hours of their onset, helping to differentiate one particular virus strain from another [II–2]. An example of this differentiation is noted in the case of the Influenza A H1N1 virus, from Influenza A H5N1. Nuclear techniques are also important in determining the nucleic acid sequence that describes the capacity of a particular virus strain to cause a disease. Different strains of the same virus may affect birds and also humans, e.g Influenza A H5N1 low pathogenicity versus Influenza A H5N1 high pathogenicity (Fig. II–1) [II–3]. The latter causes deaths in more than 60% of infected humans. The isotopic analysis of the genetic make-up of such a virus can be used by health authorities in making decisions ranging from public notification — as was the case of Influenza A H1N1 (low pathogen) — to immediate pandemic action in the case of Influenza A H1N1 (high pathogen) [II–4]. This information not only aids disease control personnel and policy makers in their attempts to control and eliminate veterinary and public health pathogens, but also forms the basis for decision making that affects transboundary trade and travel.

Radioisotope labelled assays that use isotope levels that are below the limit of disposal are under development. Isotope based nucleic acid hybridization approaches are used to detect genetic material in host tissues that will allow direct identification of infected animals as well as provide information of epidemiological importance in relation to the strain type or variant of the agent. These tests depend on the preparation of suitable DNA probes labelled with sulphur-35 or phosphor-32 and their amplification in vitro by a nucleic acid amplification technique (PCR) to increase the amount of the specific target.

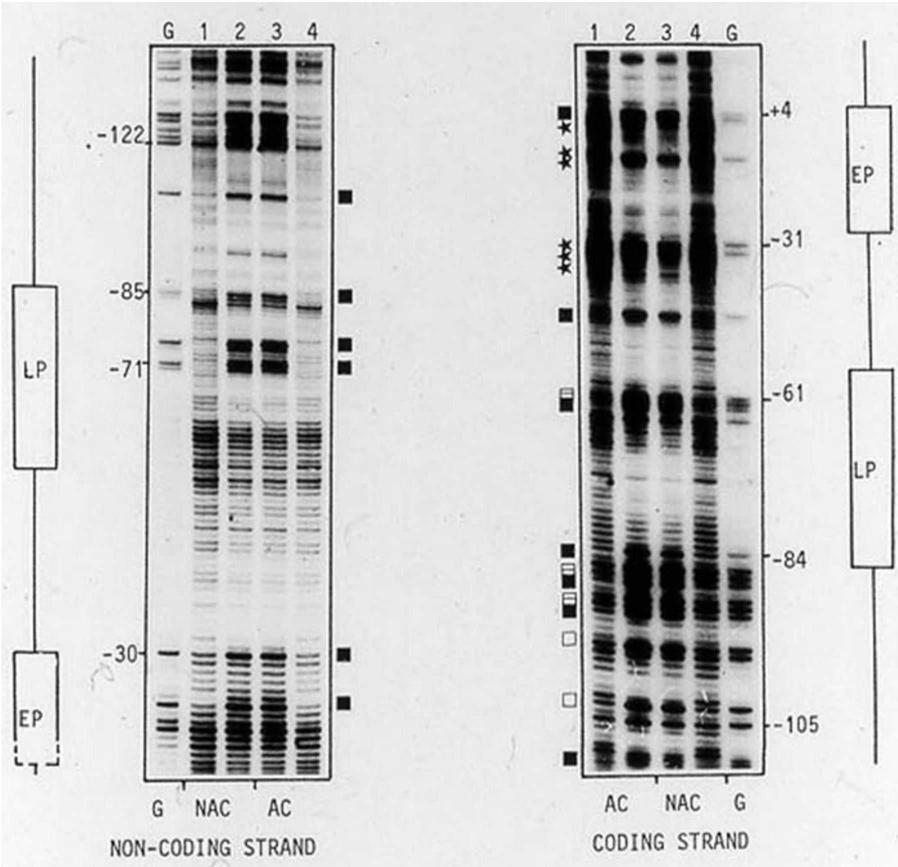

FIG. II–1. Phosphor-32 labelled protein-DNA analysis to study the operational control of active and non-active pathogenic genes to determine why certain pathogens are more aggressive than others. Nucleic acid sequence differences were observed in the late promoter (LP) and early promoter (EP) regions of the RNA transcription responsible genes of different Avian Influenza strains

Nucleic acid thermal amplification technologies shorten the time for a test result to less than a day and in many cases a result can be obtained within an hour [II–1]. Recent successes using this technology include the development of tests to diagnose diseases such as the Peste des Petit Ruminants disease and capripox virus disease (the collective word for goat pox, sheep pox and cattle pox viruses) and in the sequencing of the different genomes. To set up an appropriate control against the outbreak of one of the three pox viruses in a livestock herd, the outbreak virus needs to be identified. Currently, the capripox virus family,

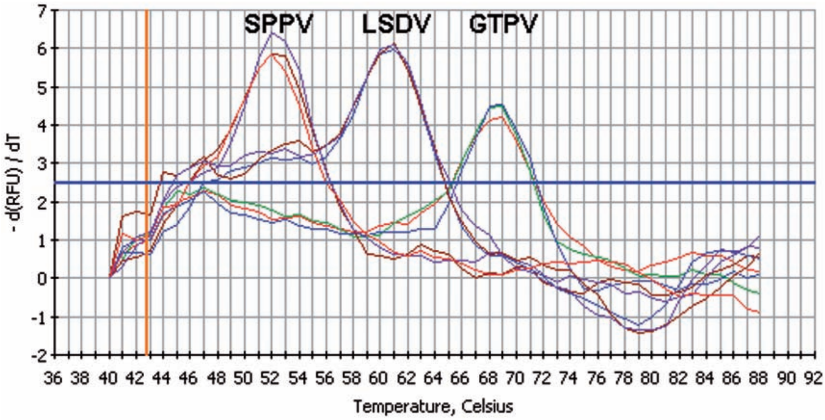

FIG. II–2. Discrimination of sheep pox virus, cattle pox or lumpy skin disease virus and goat pox virus based on their genetic sequence differences is possible using molecular DNA thermal amplification technologies. The Y axis indicates the signal amplitude and the X axis the temperature in degrees Celsius.

although closely related, requires three different vaccines for protection, i.e. there is no cross-protection between the different capripox virus strains. Sheep pox virus, goat pox virus and cattle pox or lumpy skin disease virus, the third member of the capripox virus genus (Fig. II–2) can be differentiated using the nuclear related thermal amplification real-time PCR approach, thereby selecting the correct vaccine to protect against the homologous pathogen [II–5].

Nuclear technologies are also vital to animal disease diagnosis where rapid decision making would be an advantage, and especially in situations where the suspected disease occurs in difficult to reach or remote areas that are far from the laboratory [II–1]. The time saved by determining whether a disease is present or not, could be the difference between containing a disease at its point of origin and protecting human lives or preventing the spread of a disease to an animal market place or further afield. Conventional molecular techniques including thermal amplification or PCR require sophisticated, expensive equipment (Fig. II–3). A robust test at the molecular level, i.e. the loop mediated isothermal amplification (LAMP) PCR, has been developed using nuclear techniques, which is a more cost effective alternative to thermal DNA amplification. The LAMP PCR can be carried out within 30–60 minutes in a simple water bath at constant temperature and the presence or absence of the isothermally amplified DNA product can be detected visually, i.e. a change in colour (Fig. II–4). Another advantage of the LAMP PCR platform is that it can be developed for use on-site or on-farm as a penside (point of care) rapid diagnostic test [II–1].

FIG. II–3. Different models of thermal DNA amplification cyclers (PCR machines). Isothermal DNA amplification technologies will reduce reliance on this expensive equipment.

II–3. Migratory connectivity: Using stable isotope analysis to determine the role that wild birds play in disease outbreaks

A unique use of nuclear techniques is the ability to trace wild birds in order to determine if and whether they may contribute to the spread of the bird flu. Highly Pathogenic Avian Influenza (HPAI — Influenza A, H5N1 Bird Flu) causes disease and death in wild birds and poultry, and can also affect humans. HPAI outbreaks have resulted in losses of hundreds of millions of birds and caused serious economic damage to the poultry industry worldwide. In addition, bird flu is a zoonotic disease with a high mortality in humans, and consequently has led to the death of several hundred people. Historically, similar influenza epidemics have killed millions of people, and the threat of a pandemic disease caused by bird flu today, makes it one of the most important animal and human health hazards currently facing humanity [II–3]. There is evidence that wild birds can be infected with bird flu and it is possible that migratory wild fowl could play a role in its dissemination (Fig. II–5).

FIG. II–4. Visible colour changes in reaction tubes allow discrimination of positive and negative results when using the isothermal DNA amplification or LAMP PCR for diagnosing avian influenza.

Given the potential for wild birds to spread bird flu, more information is required about their movement. Millions of birds fly each year to and from over-wintering sites and a more concerted effort is required to investigate the poorly known routes of migrant birds in Africa, the Americas, Asia–Pacific, Central Asia and Europe. An ideal approach is to use a non-invasive stable isotope analysis (SIA), to establish the origin and flight-path of a migratory bird [II–6, II–7].

Stable isotopes are currently used for tracing food origin. They provide a unique signature to a specific location, based on the availability of the isotope, which is also incorporated into animal products [II–6]. Their signature composition is dependant on the soil, water and plant chemical composition of each location. This feed and water signature is unique to each location and can be traced in the deposits (e.g. feathers) of the birds [II–7]. A small number of natural isotopes are involved in important biological and ecological processes. They are measured by mass spectrometry to determine isotopic differences relative to international standards and reported as ratios in delta (δ) units as parts per thousand. Of most interest are the hydrogen (δD)

FIG. II–5. The origins and flightpath of migrating bar headed geese can be established by using stable isotope analysis of flight feathers.

ratios found in metabolically inert, seasonally grown tissues, such as feathers and claws that accurately reflect the ratios in lakes, rivers and oceans and in groundwater in the migratory path of the birds. The isotopic signatures of a few individuals are representative of an entire population, hence any of the individuals from that population can provide information on movement. Feathers retain this information until replaced or moulted, which typically occurs only once per year. If the isotope profile of a particular bird population is known, any individuals from that population can provide information on the global migration of that species [II–8].

The hydrogen isotope composition of potable water varies spatially across the globe but global grids of hydrogen water isotopes have been constructed that can then be compared to animal samples of known or unknown origin. These grids are constructed using data from the IAEA's Global Network for Isotopes in Precipitation (GNIP). Collecting isotope data from feathers of migratory bird species will reveal migration patterns; enable identification of the breeding areas of birds sampled in intermediate stopover sites; and in samples collected from disease outbreak sites, might provide greater understanding of the role that wild birds play as carriers of disease [II–9]. Currently, measurements of stable isotopes are done using costly isotope ratio mass spectrometry (IRMS) systems that require a well-equipped laboratory. However, newly introduced analysers (Fig. II–6) with near infrared laser technology are small, transportable and require low maintenance, making it more affordable to measure isotopes. There are currently no conventional techniques which allow this kind of tracing of diseases.

FIG. II–6. A low cost answer to isotope ratio mass spectrometry (IRMS). This stable water isotope analyser uses an infrared laser for measurement.

II–4. Radiation inactivation: The future 'gold standard' in vaccine development

Vaccination is a cost effective way of preventing and controlling disease. Although anti-viral and anti-bacterial vaccine development has been successful, there are few vaccines for parasitic diseases because of the risk of further infection by active parasites in the vaccine. The inactivation of pathogens via irradiation is promising because it is a reliable method of applying a safe vaccine — 100% inactivated — against pathogenic diseases [II–10]. Their potency has been tested and success has been achieved with the advent of the first human radiation attenuated anti-parasite vaccine for malaria. For many pathogens, a relatively low dose of gamma irradiation from a cobalt-60 source is sufficient to inactivate the organism, e.g. malaria irradiation at 150 rad, *Fasciola* irradiation at 30 Gy, and *Brucella* irradiation at 6 kGy, while viral pathogens require higher doses, e.g. RVF irradiation at 25kGy.

This opens a new approach to immunization, especially when dealing with problematic diseases, like Rift Valley Fever and various helminth (parasitic worms) and protozoal (unicellular parasites) diseases [II–11, II–12]. There is a considerable body of evidence to suggest that radiation attenuated or radiation inactivated vaccines are a safer as well as a more effective and feasible gold standard for vaccine efficacy. Conventional alternative vaccines, such as recombinant vaccines, have not yet lived up to their promise to achieve comparable levels of protection to those of irradiated vaccines, in essence to deliver effective vaccines.

Diseases caused by the liver fluke parasite *Fasciola spp* are important due to their worldwide negative economic impact and zoonotic nature; an irradiated vaccine is technically feasible. *Schistosoma bovis* and *S. japonicum* present additional targets for radiation attenuated vaccines for livestock [II–10]. The life cycles of all of these parasites are similar, involving snail intermediate hosts that produce the infective stages, which could be target immunogens for vaccine development. Studies in Sudan with *F. gigantica* have shown promise in protecting cattle, and demonstrate the technical feasibility to adapt the process to field application. The basic parameters of radiation dose, numbers of parasites, immunization route and numbers of immunization doses have already been established. Efforts can now be concentrated on developing pilot manufacturing techniques. Similar promising results have been obtained with *S. japonicum* — an important zoonosis in China — though diseases caused by pathogenic animal trypanosomes affect livestock productivity in other parts of Asia, Africa, and South America. Parasite attenuation requires optimization of the radiation dose to generate metabolically active, non-replicating parasites that are able to promote immune responses in skin and draining lymph nodes without leading to parasite invasion of the bloodstream.

Gamma irradiation inactivates viruses, but leaves the viral proteins in their native conformation thereby greatly enhancing their immunogenicity and efficacy. The reduction in effective virus particles (or its titre — measure of concentration) due to inactivation would be less for irradiation than for chemical treatment (i.e. the irradiated viruses look like native viruses but cannot cause disease) and therefore should elicit a more potent immune response [II–10, II–11, II–12]. This could impact the cost of manufacture and result in dose sparing in relation to virus production. In addition, flow-through methods of irradiation rather than batch processing will need to be developed for viral inactivation or attenuation. It would also facilitate easier monitoring of the inactivation process by means of in vitro culture. For some viral vaccines where there is poor protection, i.e. where the vaccine is not eliciting a protection, [II–10, II–11] and the safety margin is small, i.e. where the vaccine is not safe for use and needs to be administrated together with an antibiotic agent, e.g. bovine babesiosis [II–12], irradiation will lead to safer and more cost effective products. Irradiation would also speed up the production processes and be useful in dealing with emergency situations as well as in providing better quality control and assurance in terms of standardisation and immunogenicity of vaccine strains.

In addition, it is foreseen that gamma irradiation will increasingly be used in the preparation of pathogenic viruses for use as antigen in diagnostic tests like RVF Immunoglobulin G and Immunoglobulin M assays, to ensure innocuity of biological material or in the preparation of diagnostic kits to extend their shelf life.

II–5. Conclusion

The world continues to demand more and healthier animals and animal products that are environmentally safe, clean and ethical. This demand poses far-reaching challenges for animal scientists on the critically important need to improve technologies in animal production and health in order to ensure food security, poverty alleviation and environmental protection on a global scale.

Nuclear applications drive modern biotechnological research by providing more sensitive, specific and cost effective diagnostic platforms or assays to detect and characterize disease pathogens. The application of nuclear technologies — in combination with conventional technologies — contributes to improvements in the number, condition and health of animals resulting in improved livelihoods of millions of people worldwide.

Alongside advances in animal health, nuclear applications in animal reproduction and breeding show promise in assisting smallholder farmers worldwide in ensuring sustainable livestock production. The much anticipated revelation of the first bovine genome sequence and map, published in *Science* in April 2009, is a step forward in improving and utilizing animal genetic resources. With important input from scientists at the IAEA, cattle genome sequencing will contribute to the understanding and utilization of indigenous breeds to improve worldwide livestock productivity.

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Annex III

NUCLEAR AND ISOTOPIC TECHNIQUES FOR MARINE POLLUTION MONITORING

III–1. Introduction

The greatest natural resource on the Earth, the world's oceans, is both the origin of most life forms and the source of survival for hundreds of millions of people. Pollution of the oceans was an essential problem of the 20th century that was associated with the rapid industrialization and unplanned occupation of coastal zones It continues to be a concern in the 21st century. The most serious environmental problems encountered in coastal zones are presented by runoff of agricultural nutrients, heavy metals, and persistent organic pollutants, such as pesticides and plastics. Oil spills from ships and tankers continually present a serious threat to birds, marine life and beaches. Also, many pesticides that are banned in most industrialized countries remain in use today, their transboundary pathway of dispersion affecting marine ecosystems the world over. In addition to these problems, ocean dumping of radioactive waste has occurred in the past, and might occur again, with authorised discharges of radioactive substances from nuclear facilities into rivers and coastal areas contributing to the contamination of the marine environment.

A transboundary issue, marine pollution is often caused by inland economic activities, which lead to ecological changes in the marine environment. Examples include the use of chemicals in agriculture, atmospheric emissions from factories and automobiles, sewage discharges into lakes and rivers, and many other phenomena taking place hundreds or thousands of kilometres away from the seashore. Sooner or later, these activities affect the ecology of estuaries, bays, coastal waters, and sometimes entire seas, consequently having an impact on the economy related to maritime activities.

To ensure the sustainable use of marine ecosystems it is necessary to measure critical contaminants individually and to obtain reliable data on their source, dynamics and fate. Nuclear and isotopic techniques provide a unique source of information for identifying nuclear and non-nuclear contaminants and tracing their pathways in the environment, as well as for investigating their biological effects. This review provides a short summary of the application of nuclear techniques and isotopes as tools to track the source of contamination. Emphasis is placed, in particular, on the use of nuclear techniques for the determination and the tracking of organic pollutants.

III–2. Tracking contaminants in the marine environment through the application of isotopic tracers

Determining pollution sources is one of the biggest issues in evaluating the incidence and severity of contaminants in the marine environment. For the past 50 years, the impact of human activity has aggravated environmental conditions in marine ecosystems. In effect, a wide range of waste and discharge emerging from industries and activities undertaken at the local, sub-regional and regional levels combine in the world's ocean currents, resulting in a global distribution of contaminants. To curb these phenomena it is imperative for countries to apply environmental regulation that considers socioeconomic development on par with environmental protection at local and global scales. However, effective environmental regulation can only be accomplished if contaminant distributions are clearly linked to known processes or sources. Stable carbon isotope analysis can help track sources of organic pollutants. The stable isotopic composition of a contaminant in the environment is the end result of a composite sequence of events. Chemicals produced from distinct sources by essentially different processes are expected to exhibit specific isotopic compositions that can be used to identify sources.

One of the most significant advances in analytical chemistry in the past few years has been the development of individual compound specific stable isotope analysis (CSIA). This technique, which is based on gas chromatography/isotope ratio mass spectrometry (GC/IRMS) allows for the measurement of the carbon isotopic composition of individual compounds within a complex mixture. CSIA of carbon is being used to uniquely identify naturally occurring pollutants, such as polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, polychlorinated biphenyls (PCBs) and crude oils and refined hydrocarbon products. GC/IRMS can be used to measure the nitrogen and hydrogen isotopic composition of individual compounds. The ability to monitor more than one isotopic composition greatly improves the ability to identify the sources and processes controlling contaminant behaviour in the environment. While GC/IRMS systems are not yet available to measure the chlorine isotopic composition of individual chlorinated contaminants, chlorine isotope analysis is a useful technique for studying the sources and fate of common chlorinated contaminants. Molecular level radiocarbon (carbon-14 (C-14)) analysis of compounds is also used to determine compounds that are either natural products or derived from industrial synthesis.

III–2.1. Hydrocarbons and oils

Hydrocarbons and oil products are a group of pollutants that have complex and diverse composition and which cause various impacts on living organisms — from physical and physicochemical damage to carcinogenic effects. The estimated average annual amount of oil entering the marine environment from ships and other sea-based activities, based on data from 1988–1997 is 1 245 200 tonnes/year [III–18]. Until recently, source apportionment studies of hydrocarbons in the environment mostly relied on molecular fingerprint recognition. Nevertheless, processes affecting hydrocarbons in the marine environment (evaporation, dissolution, photo-oxidation, biodegradation, etc.) might alter the initial hydrocarbon molecular profiles due to the preferential compound losses or degradation, increasing the chances of ambiguity in using molecular profiles in source identification.

Petroleum genesis induces a wide range of isotopic signals, which in general differ significantly from the isotopic compositions of unpolluted marine ecosystems. The complex isotopic fractionation patterns induced by physical and biological processes result in characteristic carbon-13/carbon-12 ratios that can be used to classify crude oils, petroleum products and tars. While most emphasis has been placed on the use of bulk carbon isotopes for source and correlation purposes, a number of forensic applications include other stable isotopes. Sulphur, nitrogen and deuterium isotopic abundances also reflect source and geological histories of formation, which contain oil-field specific ratios. The characteristic isotopic ratios of these elements can be exploited to ‘fingerprint’ oils spilled into the environment in order to determine the source or sources. While bulk measurements provide useful information, the compound specific isotope analysis of individual components within a specific type of oil represents a unique signature of its origin and maturation [III–2].

In conjunction with the existing tools of biomarkers, GC–IRMS has been used for forensic identification of gasoline and crude oil spills. For example, it allows correlating hydrocarbons spilled in aquatic environments with their suspected source(s) based on comparison of the isotopic composition of individual hydrocarbons. Differences in the isotope composition of individual compounds within a gasoline or crude oil sample are immediately apparent and reflect their different origins. In this regard, although weathering can result in a remarkable loss of volatile hydrocarbons, $\delta^{13}C$ values of non-volatile and semi-volatile compounds are unaffected by weathering and their isotopic profiles can be used to identify and trace the source of an oil spill.

FIG. III–1. The red line shows the route taken by the oil carrier Prestige, from the time it started leaking oil on 2002-11-13 until it sank on 2002-11-19. The dark smudges indicate the oil spill detected by satellite remote sensing. Data compiled with nuclear techniques complemented with satellite imagery can be instrumental in identifying pollution sources.

After the Erika spill[35], bulk and individual compound isotopic analyses on oil residues sampled along the Atlantic Coast of France allowed the unambiguous differentiation of samples related to the Erika oil spill from those due to other tar ball incidents [III–3]. The CSIA of carbon was also recently used by the IAEA Marine Environment Laboratory in Monaco in conjunction with non-nuclear fingerprinting techniques to investigate the sources of the oil slicks sampled in the vicinities of the wreck more than four years after the Prestige[36] accident (Fig. III–1). The isotopic data was used to ascertain that the oil from the slicks matched the oil originally carried by the Prestige (Fig. III–2).

The measurement of hydrogen isotope ratios in specific petroleum hydrocarbons is also a powerful technique to identify the source of the contaminant since the hydrogen isotope ratios of crude oil hydrocarbons show a wide compositional variation and are conserved during aerobic biodegradation.

[35] The Maltese tanker 'Erika' broke in two parts close to the Atlantic coast of France on December 12, 1999. It is believed about 10 000 t of oil spilled into the sea.

[36] On 13 November 2002, the tanker 'Prestige' broke in two 240 km off NW Spain and sank to a depth of more than 3000 m with about 58 000 t of heavy fuel oil and leaks from several cracks in the structure.

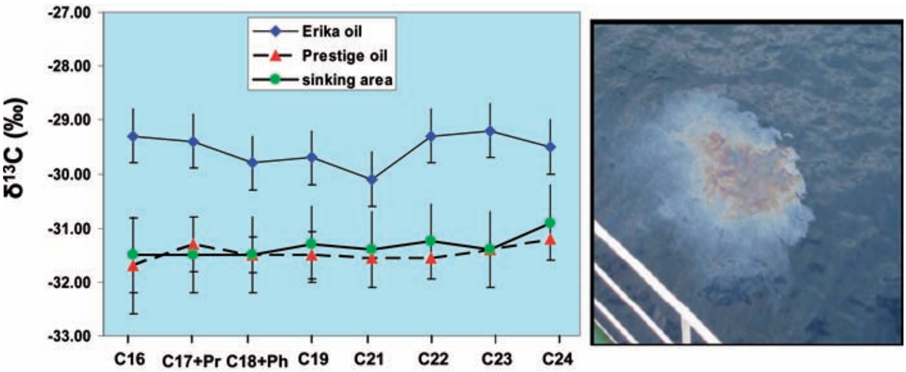

FIG. III–2. Comparison of the carbon isotopic signatures of the fuel oil found above the Prestige wreck in October 2006 with the one originally carried by the tanker in 2002 and that from the Erika ([III–3]). On the x axis the variation in C-13 is reported for the different hydrocarbons examined as reported on the y axis (Source: PhD Thesis, Elourdui-Zapatarietxe del Aguila, 2009, plus photo.)

In the future, both hydrogen and carbon isotopic data should be considered when tracing contamination sources and monitoring biodegradation.

In addition to the stable isotopes, radiocarbon (C-14) measurements can potentially provide information on oil contamination. Petroleum-derived organic matter is C-14 free, on the other hand total marine organic matter is labelled with C-14 originating from both C-14 produced naturally in the atmosphere by cosmic radiation and in nuclear weapons explosions. Therefore, the absence of the C-14 signal in contaminants derived from fossil fuel (as the complete decay during the oil's geological formation) provides a useful quantitative indication of the contribution of petroleum carbon to the total marine organic matter.

III–2.1.1. Polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are a widespread class of organic contaminants that enter the marine environment mostly due to atmospheric deposition and oil spills. They can be formed during incomplete combustion processes (pyrolitic origin) of organic matter (e.g. coal, oil, wood), and are also major constituents of crude oil (petrogenic origin). They might also derive from the biological and physiochemical alteration of organic matter, which occurs in sediments after deposition (diagenetic origin). As some PAHs exhibit mutagenic and carcinogenic properties, the knowledge of their sources is of key importance due to their eco-toxicological nature, which present long-term health effects on nearshore marine systems, affecting ecological processes, public health and social and commercial use of marine resources. In this context, molecular stable carbon isotopic composition of PAHs by GC/IRMS is a powerful tool for use in conjunction with molecular fingerprint examination for studying the sources and environmental fate of hydrocarbons in the modern environment. For instance, atmospheric contaminants from combustion source materials such as soot from biomass, natural gas, coal burning and vehicle exhausts might be tracked to source materials because of the isotope signals of the PAH products [III–1, III–5].

Other studies on carbon isotopic analysis of PAHs in sediment samples near a former gas manufacturing plant in Illinois indicated that the hydrocarbons were not the same as the tarry soil samples recovered from the gas plant [III–19]. The dominant signatures identified in the surface sediments came from a mixture of PAH sources such as coal tars and carburetted water gas tars. Source apportionment might be complex because the range of $\delta^{13}C$ values of PAHs originating from different combustion processes such as diesel, coal, gasoline, and wood burning smoke might overlap each another. However, it has been shown that distinct isotopic signatures are produced by primary petroleum and combustion-related PAH sources, as well as between the combustion of C4[37] plants using the C_4 photosynthetic pathway, termite nests or biogenic natural gas. On the other hand, radiocarbon dating of individual PAHs using off-line gas chromatography/accelerator mass spectrometry (GC/AMS) is emerging as a promising tool to apportion fossil and contemporary or biogenic sources of compounds in marine samples [III–6, III–8].

III–2.2. Halogenated organic compounds

Most of the halogenated organic compounds belong to the category of persistent organic pollutants, which have a tendency to bioaccumulate along the food chain, causing toxic and mutagenic effects. A few studies have reported the carbon-13 compound specific isotope analysis (CSIA) of commercial polychlorinated biphenyl (PCB) and polychlorinated naphthalene mixtures (PCN) such as Aroclors, Kanechlors, Phenoclors, etc., to establish baseline data for future identification of these anthropogenic contaminants. Recent studies have also detected some bipyrrolic halogenated organic compounds worldwide and accumulating in the marine food webs [III–7]. To date, it has been difficult to determine whether these compounds are natural products or derived from industrial synthesis. Radiocarbon (C-14) is a tracer used to distinguish between natural or synthetic compounds. In this context, radiocarbon analysis may be used

[37] C4 designates the photosynthetic pathway of plants that fixes carbon to produce four-carbon molecules, in contrast to the majority of plants that produce C3 molecules

as a tool to establish the origin of halogenated organic compounds since all recent natural products have modern or contemporary C-14 levels. In contrast, synthetic goods derived from petrochemical products contain no measurable C-14.

III–2.3. Perchlorate

The widespread introduction of synthetic and agricultural perchlorate (ClO_4^-) into the environment has contaminated numerous municipal water supplies — in the marine environment, contamination by this compound presents an unequivocal problem. Various potential sources of ClO_4^- are present, including agriculture (past or present), fireworks manufacture and use, military bases including missile storage and launch facilities, road-flare runoff, and lawn fertilizer, among others. Stable isotope ratio measurements of chlorine and oxygen have been applied for discrimination of different ClO_4^- sources in the environment. More recently, the characteristic chlorine-36 and chlorine-37 isotopic abundances found in the three principal sources of ClO_4^- present in the environment allowed these sources to be distinguished from each other. These results may have immediate forensic applications in delineating the sources of ClO_4^- in water supplies and foodstuffs, and they may provide important constraints for determining the natural production mechanism of ClO_4^- [III–9].

III–3. Stable isotopes to study bioremediation

In situ bioremediation has emerged as one of the most important alternatives to mitigate the damage caused by marine oil spills and other hydrocarbons. However, it is imperative that biotransformation processes are accurately understood and quantified. Quantification of intrinsic biodegradation may also reduce site remediation costs where engineered remediation is instituted. For that, the natural abundance of stable isotopes of essential elements involved in the biodegradation processes (carbon, hydrogen and oxygen) are used to monitor the occurrence of in situ biodegradation, the pathways of degradation and the rates and extent of biodegradation of fuel or chlorinated hydrocarbons. Monitoring of in situ biotransformation using stable isotopes may be achieved by the analysis of isotopic compositions: (i) of the products of degradation; (ii) the residual fractions of the contaminant; and (iii) dissolved inorganic carbon of the water, because isotopic fractionation results in preferable degradation of chemical bonds with lighter compared to heavier isotopes[38] [III–10]. Carbon dioxide produced by organic matter oxidation, inorganic carbon dissolution, or contaminant hydrocarbon degradation has characteristic C-13 isotope ratios. Their C-13 values are useful tools for the assessment of in situ biodegradation in complex environments. Furthermore, the oxygen isotopic compositions of molecular oxygen, nitrate, and sulphate in complex systems are affected primarily by microbial processes, and isotopic fractionation during microbial respiration produces a significant change in the $\delta^{18}O$ of the residual molecules. The combination of the isotopic compositions of CO_2 and O_2 help to distinguish between aerobic and anaerobic production of CO_2 and for quantifying microbial respiration rates [III–11].

In general, quantitatively differentiating the effects of bio-transformations from physical processes on contaminants is challenging. However, CSIA allows for the rapid determination of carbon and hydrogen isotopic signatures of organic compounds over the course of biodegradation by measuring the two stable isotopes of carbon and of hydrogen. CSIA is used as an indicator parameter to assess the in situ biodegradation of the chlorinated solvents and fuel oxygenates, e.g. methyl *tert*-butyl ether. In comparison with the carbon isotopes, the hydrocarbon isotopes display large variation in the deuterium isotope values. Indeed, the hydrogen isotope ratio of the light petroleum hydrocarbons can also be used to monitor in situ bioremediation of crude oil contamination.

III–4. Stable isotopes to track biomagnification of contaminants

Many persistent organic pollutants (POPs) present in the aquatic environment tend to accumulate in aquatic organisms due to their hydrophobicity. The widespread and persistent nature of these chemicals has been linked to various environmental effects, including pollution of water, sediments, and of the aquatic food chain. The health effects posed by exposure to these chemicals include disturbances ranging from disorders of the nervous or immune system, to increases in the risk of certain cancers. In the last two decades, the study of biomagnification[39] profiles of POPs including PCBs, PAHs, organotins and trace elements through aquatic food webs has been facilitated through stable isotope ratio analysis of bioelements, such as carbon and nitrogen. In general, the stable nitrogen isotope ratio $\delta^{15}N$ increases by 3–4‰ (per mille) per trophic level in a food chain. Thus, the value of $\delta^{15}N$ is suitable for determining the trophic position of each organism in a food web. The stable carbon isotope ratio, $\delta^{13}C$, is enriched

[38] The stability of a chemical bond depends on the isotopic composition. Bonds between lighter isotopes (e.g. $^{12}C–^{2}H$) are more readily broken than bonds between heavier isotopes (e.g. $^{13}C–^{2}H$).

[39] Biomagnification is the increase in concentration of a substance that occurs in a food chain as a consequence of persistence, food chain energetics and low rate of internal degradation of the substance.

slightly by about 1‰ per trophic level, enabling its use in identifying primary carbon sources in a food web [III–12].

III–5. Use of isotope labelling to study the fate of contaminants

Understanding contaminant input routes, transport mechanisms and environmental conditions provides the basis for determining the fate of contaminants. This permits the explanation and anticipation of contaminant impacts on environmental biodiversity and human health. Data on the environmental fate of contaminants are required in order to determine the potential of a pollutant to reach coastal waters, including information on its hydrolysis, photolysis and aquatic metabolism. The introduction of a labelled tracer into a controlled experimental system permits the investigation of the interaction of individual contaminants with biotic and abiotic components of the environment. Classically, C-14 labelled xenobiotics[40] are applied to study the fate of organic compounds in laboratory mesocosms[41]. The radioactivity of the label is used to trace the mineralization ($^{14}CO_2$), the portion of extractable material and to quantify the part of the label incorporated within the sediment bound residues or accumulated into the organisms. Compared with the C-14 technique, the C-13 labelling method allows for direct structural assignments of the compounds by mass spectrometry, easy handling and can be performed in the field.

III–6. Stable isotopes to study eutrophication

The rise in the human population in coastal watersheds and changes in land use has led to increases in the delivery of nutrients in aquatic environments. The resulting eutrophication of coastal waters has many adverse effects in the marine environment, through disturbance of ecological balances and fisheries, and through interference with recreational activities and quality of life. Eutrophication — nutrient enrichment leading to elevated production of particulate organic matter — is one of the profound impacts caused on coastal ecosystems by human activity. Increased nutrients loading can lead to blooms of toxic red tides including enhanced primary production, changes in community structure, increases in sedimentation and oxygen consumption, oxygen depletion in the bottom water and sometimes the death of benthic animals and fish. These

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[40] Chemical found in an organism, but not normally produced or expected to be present in it.

[41] A mesocosm refers to “an experimental system that simulates real-life conditions as closely as possible, whilst allowing the manipulation of environmental factors”.

adverse effects have prompted the search for suitable indicators of eutrophication to assess water quality of aquatic ecosystems [III–13]. Stable nitrogen isotope ratios ($^{15}N/^{14}N$; i.e. $\delta^{15}N$) have been widely used as indicators of anthropogenic eutrophication in aquatic ecosystems. Sewage water typically has a high nitrogen stable isotope ratio ($\delta^{15}N$) due to denitrification during the treatments. Applications of nitrogenous fertilizer to agricultural farmlands lead also to an enhancement of soil denitrification and increase the $\delta^{15}N$ in groundwater. In contrast, the $\delta^{15}N$ of nitrogen derived from atmospheric deposition and nitration fixation by bacteria are much lower. Groundwater and sedimentary organic matter with an elevated $\delta^{15}N$ appears to act as an indicator of the level of anthropogenic nitrogen loads to coastal waters, and the $\delta^{15}N$ delivered to the coastal waters are transferred to the food chain. Nitrogen isotope ratios of marine producers may be used to identify incipient eutrophication in coastal waters.

The dual isotope analysis of nitrate (NO_3^-) in water ($\delta^{15}N$ and $\delta^{18}O$) is used to further differentiate sources of nitrate when $\delta^{15}N$ ranges overlap. For example, $\delta^{18}O$ can be used to separate NO_3 fertilizer from soil nitrogen and ammonia (NH_4) in fertilizer and rain. Additionally, both the $\delta^{18}O$ and $\delta^{15}N$ of the residual nitrate increase systematically as a result of denitrification. Other isotopes, e.g. sulphate oxygen and sulphur isotopes in river water might also enable the discrimination between natural (geological, sea water, geothermal and volcanic) and anthropogenic sources such as fertilizers. Employment of more than one isotopic proxy will allow for a more accurate identification of the nutrient sources available to primary producers.

The analysis of proxy records preserved in sediments often provide the only way to reconstruct environmental change in areas impacted by eutrophication and to establish pre-impact baselines. Stable carbon isotope ratios in microfossils provide a tool for reconstructing historical environments, in particular organic carbon delivery to sediments. Increased organic matter inputs typically lead to a decrease in C-13 in the carbonate shells with a concomitant C-13 increase in the organic matter. Furthermore, the main indicator of enhanced primary production linked to eutrophication is phytoplankton. Their remains, and the specific chemical markers derived from them (e.g. lipid biomakers) [III–14], can be used to track changes in plankton communities in response to eutrophication. Moreover, since eutrophication leads to raised C-13 values due to increased marine phytoplankton production, the compound specific carbon isotope analysis of lipid biomarkers reflect the strength of the eutrophication.

III–7. Use of radioisotopes for the detection of toxins in harmful algae blooms (HABs)

One of the most worrisome manifestations of HABs is that certain algal species produce toxins that can accumulate in seafood products (predominantly shellfish and fish) and then pose a risk to human consumers. Fig. III–3 shows a map of the regions affected by the phenomena of HABs and the increase of HABs events worldwide.

The heterogeneity within and among toxin classes makes toxin detection and quantification challenging. Different species of algae — examples are shown in Fig III–4 — produce different types of toxins. Numerous approaches to toxin detection have been developed, generally categorized as whole animal (in vivo) bioassay, in vitro bioassays, and quantitative instrumental analysis. One useful technique of analysis employs radioisotopes — the receptor binding assay (RBA). The RBA is a technique based on the function, or pharmaceutical activity of the toxins — i.e. the highly specific interaction of a toxin with a biological receptor. For example, the saxitoxins (STXs) are toxic because they bind to and block sodium channels in certain types of human tissues, disrupting muscle function and leading to paralysis and death. The sodium channel is the logical receptor to be used in a receptor binding assay for STXs. RBAs have been developed for toxins that affect the sodium channel (PSP, NSP and CFP toxins) [III–15, III–17] and glutamate receptor (ASP toxins) [III–15, III–16]. The binding of toxin molecules containing a radionuclide such as tritium (^{3}H) to the receptor sites is then determined by a liquid scintillator counter.

III–8. Long lived radionuclides and isotope ratios measurements

With the advent of advanced mass spectrometric (MS) techniques, long lived radionuclides determination is no longer performed by counting decays, but by employing MS techniques because of their outstanding capacity to determine precise and accurate isotopic abundances and isotopic ratios. Isotope ratio measurements have been applied increasingly for investigating the fine isotope variations in nature, age dating of geological samples, provenance determination of environmental contamination, nuclear material accounting and pollution control, and for biological studies with tracer experiments. Applied to marine ecosystems, the technique assists in determining and tracking sources of contamination. Moreover, mechanisms of transport of contaminants as well as their accumulation/desorption from sediments can be followed.

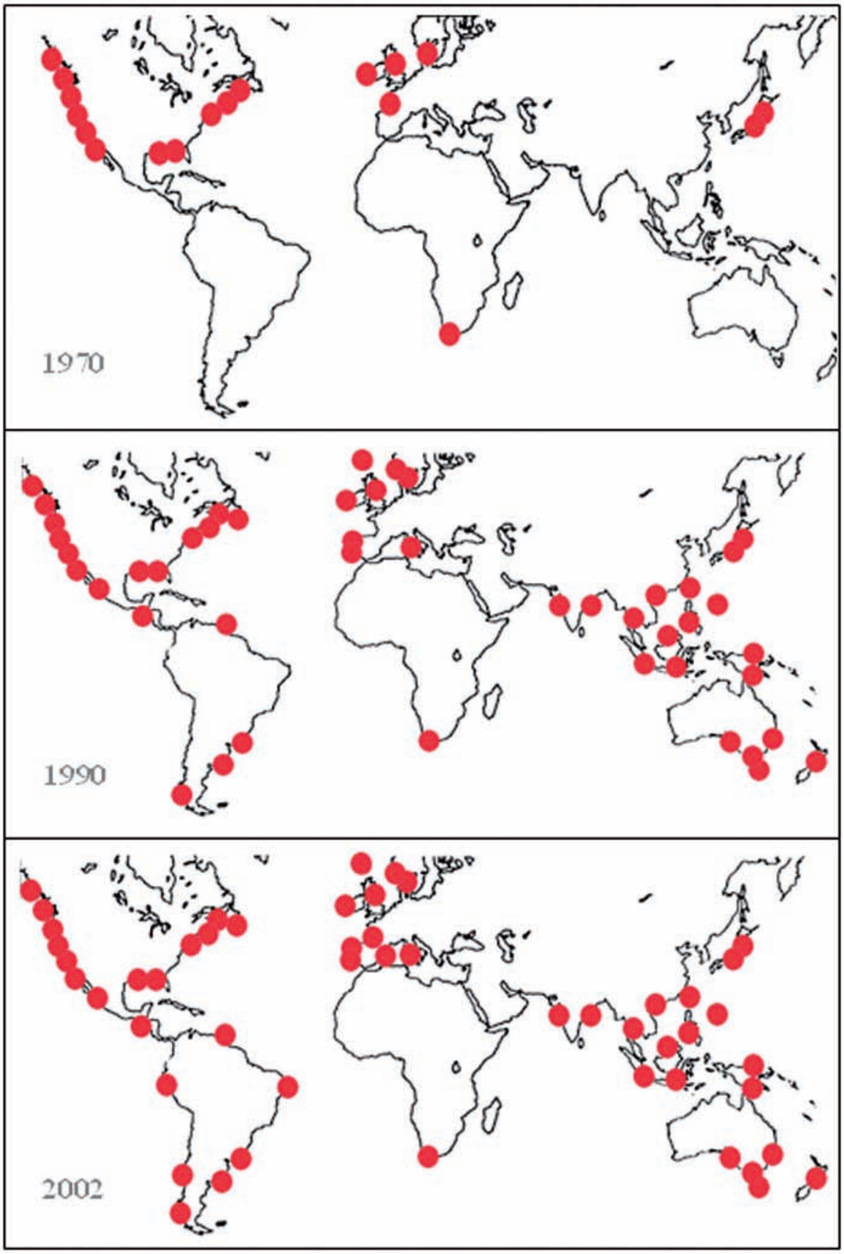

FIG. III–3. Harmful algal blooms — a growing concern worldwide — produce toxins that accumulate in marine species rendering them unfit for human consumption (data from IOC-UNESCO).

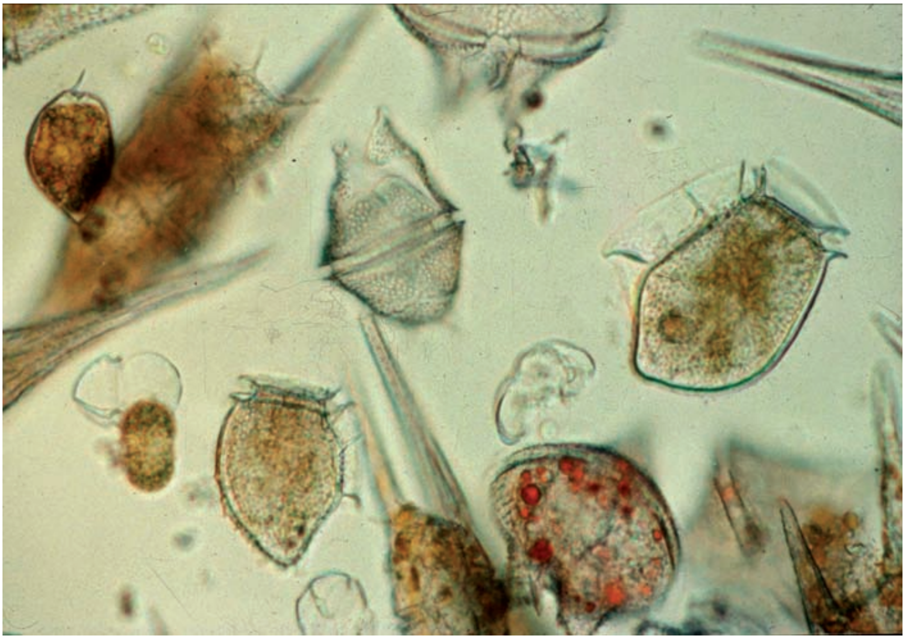

FIG. III–4. Example of harmful microalgae.

Recent developments in mass spectrometry with the developments of better performing magnetic sectors and their coupling to electrostatic sectors have brought a new dimension to this field. In addition to its simple and robust sample introduction, high sample throughput, and high mass resolution, the flat-topped peaks generated by this technique provide for accurate and precise determination of isotope ratios. These features, in combination with the ability of the inductively coupled plasma source to ionize nearly all elements in the periodic table, have resulted in an increased use of inductively coupled plasma–mass spectrometry (ICP–MS) for such measurements in various sample matrices. Moreover, the technique can be coupled with chemical separation on-line methods such as liquid chromatography, allowing a fast throughput of samples avoiding manual radiochemical separations. Figure III–5 shows the simultaneous separation and determination of actinides and lanthanides in marine sediment by ICP-MS on-line coupled to a chromatographic system

The ability to measure isotope ratios allows also the use of isotope dilution as a calibration strategy in ICP-MS, along with the more common approaches of external calibration and the standard additions. An isotope ratio is far more robust than a signal intensity, which makes isotope dilution mass spectrometry (IDMS)

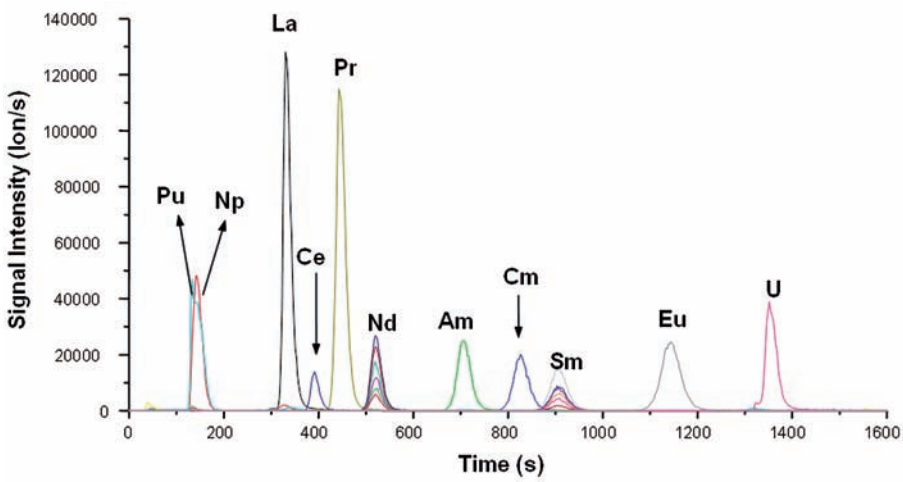

FIG. III–5. Simultaneous chromatographic separation and on-line mass spectrometric determination of lanthanides and actinides in a marine sediment sample. This is instrumental in determining isotope ratios that are important in identifying and tracking sources of contamination. (Source: BETTI, M., ITU Summer School 2003 on 'Actinide Science and Applications'; EU Joint Research Centre — ITU, Karlsruhe.)

a very reliable approach. When carried out with the utmost care and control of all factors affecting the final uncertainty, IDMS provides highly accurate and precise results and therefore is the best calibration strategy for certification measurements in the production cycle of various certified reference materials.

III–9. Radiometric dating/radiochronology

Historical records of organic and inorganic pollution combined with isotopic fingerprinting of contaminant sources are a powerful argumentative tool to link the evolution of contaminants with socioeconomic decisions. An investigation conducted by scientists from Cuba and the IAEA, examined whether pollution in the marine sediment environment was responsible for a ten-year decrease in lobster catch in Batabano Bay (Cuba). The first conclusion derived from the dating and pollution measurements of this study is that in general pollution levels in the Batabano Bay are very low and have not significantly changed during the period of interest, except for some local hotspots. The study demonstrates that in order to reconstruct changes in pollution over time environmental archives (i.e. marine sediments, corals) are helpful as they store information on the pollution during the geological past. A record of pollution is obtained by combining age dating with the measurements of the pollutant of interest.

Most age dating techniques are based on the radioactive decay rates of the different radionuclides present in the system. In Table III–1 the most common dating techniques are presented.

Three kinds of radionuclides are normally used for age dating of marine archives: anthropogenic, cosmogenic and natural radionuclides. The first significant appearance of anthropogenic radionuclides — e.g. caesium-137 (Cs-137) and plutonium — in the environment was a result of atmospheric nuclear bomb tests, which peaked in 1963. Thus, the first appearance of Cs-137 in sediments can be used as a time marker. Cosmic radiation interacts with our atmosphere and forms so called cosmogenic radionuclides such as C-14 and beryllium-10 (Be-10) by particle reaction. Carbon combines with O_2 and is incorporated into living organisms. When the organism dies, the C-14 concentration in the dead organism will be a function of time and can consequently be used in radiochronology. For minerals C-14 cannot be used as it is not incorporated in the matrix. For such material the uranium, and thorium decay series and primordial radionuclides (e.g. potassium/argon (K-40/Ar-40) decay system) are applied for age determination. The dating technique based on lead-210 (Pb-210) is frequently applied for dating of recent (<100 years) sediments. Table III–1 summarizes the most common applications.

In addition, one technique called luminescence dating can be used for mineral material. Not based on the measurements on the decay rate, rather, this technique uses the ionizing absorbed dose for measurement.

III–10. Conclusion

The unique diagnostic power of isotope studies can help to understand the threats to the marine environment. Most major pollution problems facing the marine environment can only be investigated using nuclear and isotopic techniques, which offer the diagnostic and dynamic information needed to identify the source of contamination, its history of accumulation, its environmental pathways and its impact on the environment. Such information is needed to make cost effective mitigation decisions.

TABLE III–1. THE MOST COMMON APPLICATIONS FOR RADIOMETRIC DATING/RADIOCHRONOLOGY

Dating technique	Application and range	Principles	Further reading
Anthropogenic radionuclide (Cs-137, plutonium)	Sediments, past ~50 years	Time of release of anthropogenic radionuclides from, e.g. nuclear facilities set a time marker in environmental archives.	Environmental records of anthropogenic impacts on coastal ecosystems: An introduction, SANCHEZ-CABEZA, J.-A., DRUFFEL, E.R.M., Marine Pollution Bulletin, 59 4–7 (2009) 87–90.
Pb-210	Sediments, <100 years	The decrease of Pb-210 in sediments is a function of time.	IVANOVICH, M., HARMON, R.S., Uranium Series Disequilibrium: Application to Environmental Problems, Clarendon Press, Oxford (1992) 571.
C-14	Organic material, <50 000	Decay of C-14 in organisms	http://www.radiocarbon.org/ FAURE, G., Principles of Isotope Geology, Wiley, New York (1986) 589. http://www.c14dating.com/
Luminescence dating	Dating of minerals in e.g. sediments, <400 000 years	Minerals (feldspar, quartz) ‘store’ information on the absorbed dose they have received over time. This ‘memory’ can be recorded and can be translated in age information.	http://www.nclr.risoe.dk/ http://crustal.usgs.gov/laboratories/luminescence_dating/technique.html
Uranium series (Th-230/U-234, U-234/U-238) dating	Sediments, corals, <1.5 million years	Disequilibrium between daughter and parent leading to either a deficiency or an excess of the daughter nuclides which can be measured as a function of time.	http://www.onafarawayday.com/Radiogenic/index.htm IVANOVICH, M., Harmon, R.S.,. Uranium Series Disequilibrium: Application to Environmental Problems, Clarendon Press, Oxford (1992) 571.

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Annex IV

DECOMMISSIONING STRATEGIES: STATUS, TRENDS AND ISSUES

This annex summarizes what decommissioning is, alternative decommissioning strategies, the status of decommissioning projects around the world, and the factors that influence choices among decommissioning strategies.

IV–1. Introduction

After a nuclear power reactor is turned off for the last time, the initial steps toward decommissioning are not unfamiliar. The fuel is moved to the spent fuel storage pond where it will cool down for at least a few years, after which it will be moved to away-from-reactor (AFR) storage or sent for reprocessing. During those initial years, the workforce will most likely be relatively unchanged, and the systems to cool the spent fuel storage pond and ensure water quality will operate as before. Systems ranging from the reactor's instrumentation and control to heating and ventilation will all be kept running.

Subsequent steps will depend on the choice that has been made among the decommissioning strategies described in this annex. But the initial steps of powering down the reactor, disconnecting the turbine, and removing spent fuel will be familiar from maintenance and refuelling shutdowns experienced during the reactor's operating life.

While the spent fuel is cooling, the reactor's cooling fluids will be removed from the primary and secondary cooling loops, and the loops may be cleaned by running cleaning fluids through them. At this point, the reactor is in a state of 'cold shutdown', but many systems will continue running, including ventilation and radiation monitoring.

If the selected strategy is immediate dismantling, removal of the spent fuel away from the reactor building is a significant milestone. The reactor workforce can then be reduced and dismantling can begin. Dismantling will likely start with the turbine and other relatively uncontaminated components. Many components, such as pumps, valves and pipes, may have been replaced or removed for maintenance during the reactor's lifetime, and their removal for the final time will not be very different. The contamination level of each component will have to be measured and carefully recorded, but this again is not new. All dismantling will be done inside temporary tents or other containment structures to ensure that contamination is not spread.

As components are dismantled, they may be either stored on-site or shipped to their final disposal site. The sort of final disposal sites that are available will also determine whether large components are cut up or disposed of intact. Steam generators and even reactor pressure vessels have been disposed of intact. They are in fact containers, designed to high containment standards, that are uncontaminated on the outside and can therefore be transported, if they are not cut up, without special additional containers. Most of the dismantled components and rubble, however, must be transported in special containers. Most will be classified as low level waste (LLW) or very low level waste (VLLW). Some, like the reactor internals, will be intermediate level waste (ILW).

The strategy to dismantle and remove everything from the site can take 5–10 years (Fig. IV–1). The vacant site may then be valuable as a potential site for a new reactor since, other things being equal, building on a site that already has been licensed for such use will be easier than starting with a new site. Or, if no future special use is foreseen for the site, once final surveys have confirmed that all contamination has been removed, the nuclear licence can be terminated.

There are many variations on this basic outline of the decommissioning process. No two decommissioning projects are identical. This annex summarizes these variations and the reasons for such variation.

IV–2. Decommissioning status of nuclear power reactors around the world

At the end of 2009, 123 power reactors had been shut down. Of these, 15 reactors had been fully dismantled, 51 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 (see Table IV–1). The following section explains what these terms mean and outlines the reasons why different strategies are chosen for different reactors.

IV–3. Overview of decommissioning projects and strategies worldwide

There are three basic decommissioning options: immediate dismantling, long term safe enclosure followed by dismantling, and entombment, which is also called on-site or in-situ disposal [IV–1, IV–2]. Entombment has generally been limited to small installations. A variation on immediate dismantling called incremental or sequential decommissioning has also emerged recently in which dismantling is as immediate as possible subject to restricted year-by-year cash flows. This necessarily takes longer than immediate dismantling, where all funding is immediately available, and is more difficult to plan.

FIG. IV–1. Maine Yankee being dismantled.

The choice between the two main strategies, immediate dismantling and long term safe enclosure followed by dismantling, depends on many factors. This section presents examples from around the world to illustrate the variety of ways in which these factors can interact in practice in different decommissioning projects. The next section discusses each of the important factors in more detail.

In the USA, the choice of immediate dismantling for a number of reactors has been driven partly by the current availability of disposal facilities and uncertainty about the availability and costs of future disposal facilities. The availability of the necessary commercial disposal sites also allowed for the intact, and therefore less work intensive, removal of large components such as reactor vessels and steam generators (Fig. IV–2).

Électricité de France initially chose partial dismantling of its retired first-generation reactors and postponed final dismantling for 50 years. At the time, this was the most cost-effective strategy. Subsequently, however, reduced dismantling costs due to technological advances, the availability of VLLW disposal facilities, and a political interest in resolving what public opinion might consider an undesirable nuclear legacy led to the earlier dismantling of old French reactors. In Italy, political considerations also led to the acceleration of decommissioning programmes.

In Germany, 14 retired reactors are being immediately dismantled while two are being kept in a safe enclosure mode for delayed dismantling. At some sites, for example Greifswald in eastern Germany, the socioeconomic benefits of using local industry and labour in an economically depressed region were an

FIG. IV–2. Removal of the reactor vessel at Maine Yankee.

important factor in choosing immediate dismantling. The immediate availability of both on-site and off-site storage options for spent fuel and decommissioning waste also influenced the choice of immediate dismantling. In some cases large components have been cut into pieces on-site; at Gundremmingen, for example, steam generators were cut into pieces after being filled with water, frozen and turned into more manageable monoliths. In other cases, large components are being stored intact on-site, for example at Greifswald.

In Sweden, the current lack of disposal facilities for decommissioning waste has led to deferred dismantling of the Barsebäck reactors until such facilities are available.

For most reactors in Eastern Europe, current plans are to significantly defer active dismantling, due mainly to the need to build up sufficient funds. Until recently, most Eastern European countries had no financial provisions to cover eventual decommissioning, and the anticipated operating lifetimes of many reactors were insufficient to accumulate the required funds. In some cases, economic and political constraints have made it difficult to collect the required level of decommissioning funds. In most other countries with long established nuclear power programmes, existing decommissioning funds appear to be adequate. However, the long term effects of the global financial crisis that started in late 2008 have yet to be evaluated fully.

IV–4. Factors in selecting a decommissioning strategy

IV–4.1. Legislative and regulatory requirements

Different countries have different regulations governing decommissioning strategies and their timing. For example:

- Japan, to enable further use of reactor sites, requires that facilities begin total dismantling within ten years of shutdown. Facilitating reuse of available sites is an important consideration in a country where such land is at a premium.
- The US Nuclear Regulatory Commission (NRC) limits the safe enclosure period to 60 years.
- UK policy allows dismantling to be delayed for Magnox reactors and for them to be kept in a safe enclosure mode for more than 100 years. Such a long period allows levels of radioactivity to be reduced through radioactive decay so that workers could work on a Magnox reactor without limitation, and also allows the accumulation of decommissioning funds. This policy is, however, being reconsidered.

In the past ten years, nearly all countries with operating reactors have promulgated decommissioning regulations defining operators' responsibilities. A facility's operator has the primary responsibility for all technical and financial measures necessary for decommissioning and the safe handling of all material. There are, however, different approaches to the responsibility for the disposal of radioactive waste, e.g. whether disposal is under the supervision of national regulatory bodies or national agencies. In a few countries, dedicated national agencies are being made legally responsible for decommissioning nuclear facilities, i.e. they become the new licensees/operators (e.g. ENRESA in Spain, or PURAM in Hungary). The new atomic energy acts also codify requirements for initial and continuing decommissioning planning for nuclear facilities.

IV–4.2. National waste management strategies

Dismantling any radioactive facility generates different categories of radioactive waste. How much waste is generated in each category depends on the timing of dismantling operations. Deferment may reduce the amounts of intermediate level waste (ILW) and increase amounts of low level waste (LLW) or rubble and other waste that can be cleared from regulatory control. This will influence disposal arrangements and costs. Within the past ten years, several countries have introduced the category of VLLW, which is intended to accommodate most decommissioning waste at a disposal cost (per cubic metre) that is an order of magnitude less than the cost of LLW disposal. A VLLW repository opened at Morvilliers, France, in 2003 and reached full operation in 2004. Spain opened a VLLW repository in 2008 (Fig. IV–3). VLLW disposal sites are not too different from conventional landfill sites, and all phases of conditioning, packaging, transporting and disposing of the waste are greatly simplified compared to LLW. The availability of the VLLW category allows inexpensive disposal of most decommissioning waste and adds an incentive for immediate dismantling [IV–3].

Although disposal facilities now exist in many countries (Table IV–2), they do not exist everywhere. If no suitable disposal facilities for the amounts and categories of waste are available, then there are two options: maintain the facility in safe enclosure mode or dismantle the facility, condition the waste and store it on-site in appropriate temporary facilities.

FIG. IV–3. El Cabril, Spain: VLLW disposal facility.

All countries that do not have waste disposal sites have policies of long term safe enclosure for their shutdown facilities. Even countries with some waste disposal options may not have disposal options for all types of decommissioning waste. For example, the reactor building of the Vandellos nuclear power plant in Spain is being kept in safe enclosure mode partly because of the unavailability of a graphite disposal facility. The Vandellos graphite is kept in segregated vaults inside the reactor building. At Germany's Greifswald site, all wastes resulting from reactor decommissioning are being stored in large warehouses on-site pending future availability of a disposal site.

The most important regulatory requirements are related to clearance criteria. International recommendations for exemption and clearance have been issued by the IAEA [IV–4] and the European Commission [IV–5]. These specify radiological concentrations (typically, mass or surface concentrations) below which material can be considered to be non-radioactive and released from regulatory control. Such criteria are now established in many countries. In some cases they are part of the legislative framework (e.g. Germany, UK and USA), and in others they have been established for specific projects (e.g. Italy).

Materials removed from a decommissioned facility fall into four classes:

- Those that can be cleared for unrestricted reuse or disposal;
- Those that are authorized for reuse within the nuclear industry (e.g. a plant's cooling water equipment);
- Those that can be released for a specific restricted use outside the nuclear industry (e.g. as the foundation for an airport runway);
- Those that are to be stored or disposed of under radiologically controlled and monitored conditions.

The criteria defining these classes vary among countries. Where national regulations are lacking, regulators decide on a case-by-case basis.

IV–4.3. National spent fuel management strategies

Experience shows that spent fuel management strategies can strongly affect the selection of a decommissioning strategy. In particular, facilities to store, dispose of or reprocess spent fuel may not be readily available, and the fuel must therefore remain in the reactor facility. The lack of a transfer route for spent fuel may force a licensee into a safe enclosure strategy with spent fuel in the facility. In general, it is desirable to remove spent fuel off-site or to an on-site facility separate from the power plant within five years. This is the most common strategy in the USA. Several US nuclear power plants have been fully dismantled with spent fuel stored at nearby independent facilities (Fig. IV–4). Some water

FIG. IV–4. The independent spent fuel storage installation at Maine Yankee.

cooled water moderated power reactor (WWER) operators (e.g. at Paks, Dukovany and Mochovce) have built on-site wet and dry interim storage facilities.

An example of off-site storage is the transfer in the past decade of large amounts of spent fuel from Central and Eastern Europe reactors to the Russian Federation for eventual reprocessing. This paved the way for smoother and more timely decommissioning of those reactors.

IV–4.4. Planned use of the site

The choice of a decommissioning strategy may also depend on the planned future use of the site. For example:

- The owner may have a shortage of sites for new plant construction and may be forced to re-use a site for a new plant. In that case, immediate dismantling may be chosen. In Japan, for example, land is at a premium, and nuclear sites are relatively scarce.
- If the plant to be decommissioned is co-located with other operating facilities that will continue to be in service, safe enclosure may be the preferred choice. The necessary security, surveillance and maintenance for the shutdown facility could be provided by the remaining operating

facilities. Most European and US sites are large enough to accommodate new reactors next to the old ones, so that the old ones would not have to be dismantled to allow new build.

— The site re-developer may wish to consider the re-use of some of the plant facilities, for example, the cooling water equipment, the infrastructure, and some of the plant process systems, for purposes other than those for which they were originally intended or as part of a new or modified plant.

Originally, nuclear decommissioning management assumed that the goal was the final disposal of waste and restoration of the site to almost pristine ‘green field’ conditions. Today, the focus is on redevelopment and reuse. Decommissioning does not need to be seen as the endpoint of an existing facility or site, but rather as the starting phase of redeveloping or reusing the facility or site. Rising expectations about the expansion of nuclear power are starting to create pressure for the redevelopment and reuse of existing nuclear sites and ‘brown fields’.

In addition to re-using sites for new nuclear build, there are several recent examples of non-nuclear redevelopment or re-use. The turbine building of a decommissioned nuclear power plant was reused for a fossil fired power plant at Fort St. Vrain, USA. The Chinon-1 nuclear power plant in France was converted into a museum. Part of the Greifswald nuclear power plant in Germany is being converted into a biodiesel production facility (Fig. IV–5).

FIG. IV–5. Biodiesel plant construction at the Greifswald nuclear power plant, Germany.

Decommissioning plans should include the securing of facilities and sites after decommissioning until successful redevelopment and reuse, and they should identify structurally sound buildings and other property that should not be demolished. Early identification of redevelopment and re-use options can also help ensure uninterrupted employment where this is a priority [IV–6].

IV–4.5. Radiological factors

The removal of the fuel, process fluids, and operational waste from a reactor and, if practicable, from the site removes the main radiological risk presented by that facility. The remaining residual radioactivity, however, will present a smaller, but still important, risk to workers, the public and the environment during decommissioning. One argument for delayed dismantling in the past has been that a prolonged period of safe enclosure between the initial and final phases of decommissioning allowed radioactive decay which both reduced local dose rates to workers and allowed the re-categorization of some radioactive wastes.

In practice, however, technological progress over the past 10–15 years due to major breakthroughs in electronics, robotics and remote handling, has considerably reduced the need for manned access to more highly contaminated areas. This has reduced the importance of radiological factors in choosing a decommissioning strategy.

IV–4.6. Availability of technology and other resources

Although decommissioning technologies will continue to improve (Fig. IV–6), decommissioning is a mature industry. Large R&D programmes prevailed through the 1990s (e.g. at the Japan Power Demonstration Reactor (JPDR), BR-3, Gundremmingen, and nuclear fuel cycle facilities run by the US Department of Energy), but came to an end around 2000.

Decommissioning technology is generally more available in countries with more experience and larger nuclear power programmes. Such countries have significant experience and expertise related to their nuclear programmes and are likely to have decommissioning ‘markets’ with many companies offering a variety of products or services. The situation might be different in countries with less experience and smaller programmes.

Although the basic technology for decommissioning is well known and tested, special problems may be identified during the planning stages that may require special equipment, for example because of poor accessibility or high radiation levels. In such cases it may be necessary to develop special tools or

FIG. IV–6. Decommissioning technologies: a new waste monitor (left) and cold testing of a remote manipulator (right).

methods for remote operation or handling. However, generally speaking, except in extremely difficult circumstances such as Windscale or Chernobyl, technology is not a limiting factor constraining dismantling.

IV–4.7. Stakeholder considerations

Radioactive waste management institutions have become progressively more aware that technical expertise and technical confidence are insufficient, on their own, either to justify waste management solutions to a wider audience or to see them through to successful implementation. Because of generally heightened public sensitivity to environmental protection, any waste management or decommissioning decision will typically require thorough public examination and the involvement of many stakeholders. Stakeholders include, but are not limited to, waste management agencies, safety authorities, local communities, elected representatives, and technical intermediaries between the general public and decision makers. Decommissioning also includes aspects beyond waste management that are of interest to a wider range of stakeholders. The way in which local communities and the public in general are engaged in dialogue about decommissioning is likely to become an increasingly important issue.

From studies of stakeholder involvement in past decommissioning decisions, the one generality that can be drawn is that each decision is unique. The diversity of relevant social, political, economic, and cultural environments makes it difficult to develop guidance that is universally applicable. However, those planning new decommissioning projects may find in the experiences of others useful analogies that they can adapt to their own situations. On this basis, the IAEA facilitates the exchange of experiences among Member States, and the joint development and review of specific case studies [IV–7].

IV–4.8. Decommissioning cost and funding

To fully assess the economics of the life cycle of a nuclear plant, it is necessary to clearly understand decommissioning and waste management costs and make the necessary provisions for them. Available cost estimates of completed decommissioning projects for commercial nuclear power reactors range from about $100 million to $700 million. Cost estimates for future activities are necessarily uncertain, given the diversity of influencing factors catalogued in this annex, but growing experience in the decommissioning of large, commercial nuclear facilities is contributing to the improvement of cost estimates. The comparison of decommissioning projects is still difficult due to different approaches in cost breakdowns and reporting requirements, but several international working groups, sponsored by the EU, the IAEA and the OECD/NEA, are currently developing standardized definitions and structures for decommissioning cost estimates. Commercial firms now also offer proprietary strategic advice and cost estimation services for decommissioning projects, based upon experience gained from commercial decommissioning projects.

Whatever choices and decisions are made, it is the responsibility of the owner of the plant to make financial provisions sufficient to cover the costs of all stages of decommissioning, up to and including total dismantling and removal of the waste, in accordance with pertinent national legislation and funding requirements. If a long period of safe enclosure is envisaged, the forecasting of funding requirements may be uncertain because of variations in the costs of regulatory, social and industrial influences. On the other hand, deferment of dismantling may improve the financial situation by allowing time to accrue additional funds.

Over the past few decades most Member States have established legal provisions to collect and build up decommissioning funds. Most decommissioning funds for nuclear power plants are accumulated based on electricity surcharges. However, there is still little experience on how these accumulated funds will work in the long term [IV–8].

IV–4.9. Knowledge management

The final decommissioning of a nuclear facility should be considered from the earliest stage of its life cycle, and emphasis should be given to the acquisition and maintenance of all relevant records. One important lesson from decommissioning projects to date is that more attention needs to be given to managing and organizing records for decommissioning purposes, not just for operating and regulatory purposes. During detailed planning for the permanent shutdown of a facility, a dedicated effort is needed to develop a strategy for selecting and managing key records. Experience shows that insufficient attention to record keeping can be expensive (e.g. due to the need to reconstruct missing information) and may present safety problems (e.g. by making it necessary to work with unknowns).

When there are significant delays between permanent shutdown and the completion of dismantling, arrangements must be put into place to ensure that the necessary information is preserved. This refers not only to the physical preservation of information, but also to the skills needed to understand what it means and to assure timely actions [IV–9, IV–10].

IV–5. Conclusions

Technologically, decommissioning is a mature industry. Many of the steps in the process are similar to maintenance, storage or transport procedures experienced during a plant's operating lifetime. There is more uncertainty in the areas of knowledge management, funding, the availability of disposal sites and the potential reuse of decommissioned sites and facilities. Decommissioning experience is continually growing. Although no two decommissioning projects are identical, there is much to be gained from sharing experiences and, in areas like knowledge management, specific techniques that have proven to be successful. Even in the area of stakeholder involvement, where local situations can be diverse, those planning new decommissioning projects may find in the experiences of others useful analogies that they can adapt to their own situations.

TABLE IV–1. DECOMMISSIONING STATUS OF SHUTDOWN POWER REACTORS

(NO = no data available on selected strategy; UD = being dismantled or planned for near term dismantling; SE = in safe enclosure; FD = fully dismantled; ISD = in situ disposal (entombed))

Country	Unit	Type	Const. Date	Shutdown Date	Strategy	MW(e)
AM	ARMENIA-1	PWR	1969-07-01	1989-02-25	NO	376
BE	BR-3	PWR	1957-11-01	1987-06-30	UD	10
BG	KOZLODUY-1	PWR	1970-04-01	2002-12-31	UD	408
BG	KOZLODUY-2	PWR	1970-04-01	2002-12-31	UD	408
BG	KOZLODUY-3	PWR	1973-10-01	2006-12-31	UD	408
BG	KOZLODUY-4	PWR	1973-10-01	2006-12-31	UD	408
CA	DOUGLAS POINT	PHWR	1960-02-01	1984-05-04	SE	206
CA	GENTILLY-1	HWLWR	1966-09-01	1977-06-01	SE	250
CA	ROLPHTON NPD	PHWR	1958-01-01	1987-08-01	SE	22
DE	AVR JUELICH (AVR)	HTGR	1961-08-01	1988-12-31	UD	13
DE	GREIFSWALD-1 (KGR 1)	PWR	1970-03-01	1990-02-14	UD	408
DE	GREIFSWALD-2 (KGR 2)	PWR	1970-03-01	1990-02-14	UD	408
DE	GREIFSWALD-3 (KGR 3)	PWR	1972-04-01	1990-02-28	UD	408
DE	GREIFSWALD-4 (KGR 4)	PWR	1972-04-01	1990-07-22	UD	408
DE	GREIFSWALD-5 (KGR 5)	PWR	1976-12-01	1989-11-24	UD	408
DE	GUNDREMMINGEN-A (KRB A)	BWR	1962-12-12	1977-01-13	UD	237
DE	HDR GROSSWELZHEIM	BWR	1965-01-01	1971-04-20	FD	25
DE	KNK II	FBR	1974-09-01	1991-08-23	UD	17
DE	LINGEN (KWL)	BWR	1964-10-01	1979-01-05	SE	183
DE	MUELHEIM-KAERLICH (KMK)	PWR	1975-01-15	1988-09-09	UD	1219

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(NO = no data available on selected strategy; UD = being dismantled or planned for near term dismantling; SE = in safe enclosure; FD = fully dismantled; ISD = in situ disposal (entombed)) (cont.)

Country	Unit	Type	Const. Date	Shutdown Date	Strategy	MW(e)
DE	MZFR	PHWR	1961-12-01	1984-05-03	UD	52
DE	NIEDERAICHBACH (KKN)	HWGCR	1966-06-01	1974-07-21	FD	100
DE	OBRIGHEIM (KWO)	PWR	1965-03-15	2005-05-11	UD	340
DE	RHEINSBERG (KKR)	PWR	1960-01-01	1990-06-01	UD	62
DE	STADE (KKS)	PWR	1967-12-01	2003-11-14	UD	640
DE	THTR-300	HTGR	1971-05-01	1988-04-20	SE	296
DE	VAK KAHL	BWR	1958-07-01	1985-11-25	FD	15
DE	WUERGASSEN (KWW)	BWR	1968-01-26	1994-08-26	UD	640
ES	JOSE CABRERA-1 (ZORITA)	PWR	1964-06-24	2006-04-30	UD	141
ES	VANDELLOS-1	GCR	1968-06-21	1990-07-31	SE	480
FR	BUGEY-1	GCR	1965-12-01	1994-05-27	UD	540
FR	CHINON-A1	GCR	1957-02-01	1973-04-16	UD	80
FR	CHINON-A2	GCR	1959-08-01	1985-06-14	UD	180
FR	CHINON-A3	GCR	1961-03-01	1990-06-15	UD	360
FR	CHOOZ-A (ARDENNES)	PWR	1962-01-01	1991-10-30	UD	305
FR	EL-4 (MONTS D'ARREE)	HWGCR	1962-07-01	1985-07-31	UD	70
FR	G-2 (MARCOULE)	GCR	1955-03-01	1980-02-02	SE	39
FR	G-3 (MARCOULE)	GCR	1956-03-01	1984-06-20	SE	40
FR	ST. LAURENT-A1	GCR	1963-10-01	1990-04-18	UD	390
FR	ST. LAURENT-A2	GCR	1966-01-01	1992-05-27	UD	465
FR	SUPER-PHENIX	FBR	1976-12-13	1998-12-31	UD	1200
GB	BERKELEY 1	GCR	1957-01-01	1989-03-31	SE	138

TABLE IV–1. DECOMMISSIONING STATUS OF SHUTDOWN POWER REACTORS
(NO = no data available on selected strategy; UD = being dismantled or planned for near term dismantling; SE = in safe enclosure; FD = fully dismantled; ISD = in situ disposal (entombed)) (cont.)

Country	Unit	Type	Const. Date	Shutdown Date	Strategy	MW(e)
GB	BERKELEY 2	GCR	1957-01-01	1988-10-26	SE	138
GB	BRADWELL 1	GCR	1957-01-01	2002-03-31	SE	246
GB	BRADWELL 2	GCR	1957-01-01	2002-03-30	SE	150
GB	CALDER HALL 1	GCR	1953-08-01	2003-03-31	SE	198
GB	CALDER HALL 2	GCR	1953-08-01	2003-03-31	SE	35
GB	CALDER HALL 3	GCR	1955-08-01	2003-03-31	SE	35
GB	CALDER HALL 4	GCR	1955-08-01	2003-03-31	SE	198
GB	CHAPELCROSS 1	GCR	1955-10-01	2004-06-29	SE	192
GB	CHAPELCROSS 2	GCR	1955-10-01	2004-06-29	SE	35
GB	CHAPELCROSS 3	GCR	1955-10-01	2004-06-29	SE	35
GB	CHAPELCROSS 4	GCR	1955-10-01	2004-06-29	SE	35
GB	DOUNREAY DFR	FBR	1955-03-01	1977-03-01	UD	11
GB	DOUNREAY PFR	FBR	1966-01-01	1994-03-31	UD	250
GB	DUNGENESS-A1	GCR	1960-07-01	2006-12-31	SE	225
GB	DUNGENESS-A2	GCR	1960-07-01	2006-12-31	SE	225
GB	HINKLEY POINT-A1	GCR	1957-11-01	2000-05-23	SE	470
GB	HINKLEY POINT-A2	GCR	1957-11-01	2000-05-23	SE	250
GB	HUNTERSTON-A1	GCR	1957-10-01	1990-03-30	SE	300
GB	HUNTERSTON-A2	GCR	1957-10-01	1989-12-31	SE	150
GB	SIZEWELL-A1	GCR	1961-04-01	2006-12-31	SE	210
GB	SIZEWELL-A2	GCR	1961-04-01	2006-12-31	SE	210
GB	TRAWSFYNYDD 1	GCR	1959-07-01	1991-02-06	SE	390
GB	TRAWSFYNYDD 2	GCR	1959-07-01	1991-02-04	SE	250
GB	WINDSCALE AGR	GCR	1958-11-01	1981-04-03	UD	24
GB	WINFRITH SGHWR	SGHWR	1963-05-01	1990-09-11	UD	92

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Country	Unit	Type	Const. Date	Shutdown Date	Strategy	MW(e)
IT	CAORSO	BWR	1970-01-01	1990-07-01	UD	860
IT	ENRICO FERMI (TRINO)	PWR	1961-07-01	1990-07-01	UD	260
IT	GARIGLIANO	BWR	1959-11-01	1982-03-01	UD	150
IT	LATINA	GCR	1958-11-01	1987-12-01	UD	153
JP	FUGEN ATR	HWLWR	1972-05-10	2003-03-29	UD	165
JP	HAMAOKA-1	BWR	1971-06-10	2009-01-30	UD	515
JP	HAMAOKA-2	BWR	1974-06-14	2009-01-30	UD	806
JP	JPDR	BWR	1960-12-01	1976-03-18	FD	12
JP	TOKAI-1	GCR	1961-03-01	1998-03-31	UD	137
KZ	BN-350	FBR	1964-10-01	1999-04-22	SE	52
LT	IGNALINA-1	LWGR	1977-05-01	2004-12-31	UD	1185
LT	IGNALINA-2	LWGR	1978-01-01	2009-12-31	UD	1185
NL	DODEWAARD	BWR	1965-05-01	1997-03-26	SE	55
RU	APS-1 OBNINSK	LWGR	1951-01-01	2002-04-29	NO	5
RU	BELOYARSKY-1	LWGR	1958-06-01	1983-01-01	NO	102
RU	BELOYARSKY-2	LWGR	1962-01-01	1990-01-01	NO	146
RU	NOVOVORONEZH-1	PWR	1957-07-01	1988-02-16	NO	197
RU	NOVOVORONEZH-2	PWR	1964-06-01	1990-08-29	NO	336
SE	AGESTA	PHWR	1957-12-01	1974-06-02	SE	10
SE	BARSEBACK-1	BWR	1971-02-01	1999-11-30	SE	615
SE	BARSEBACK-2	BWR	1973-01-01	2005-05-31	SE	615
SK	BOHUNICE A1	HWGCR	1958-08-01	1977-02-22	UD	93
SK	BOHUNICE-1	PWR	1972-04-24	2006-12-31	UD	408
SK	BOHUNICE-2	PWR	1972-04-24	2008-12-31	UD	408
UA	CHERNOBYL-1	LWGR	1970-03-01	1996-11-30	SE	740

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Country	Unit	Type	Const. Date	Shutdown Date	Strategy	MW(e)
UA	CHERNOBYL-2	LWGR	1973-02-01	1991-10-11	SE	925
UA	CHERNOBYL-3	LWGR	1976-03-01	2000-12-15	SE	925
UA	CHERNOBYL-4	LWGR	1979-04-01	1986-04-26	SE	925
US	BIG ROCK POINT	BWR	1960-05-01	1997-08-29	FD	67
US	BONUS	BWR	1960-01-01	1968-06-01	ISD	17
US	CVTR	PHWR	1960-01-01	1967-01-01	UD	17
US	DRESDEN-1	BWR	1956-05-01	1978-10-31	SE	197
US	ELK RIVER	BWR	1959-01-01	1968-02-01	FD	22
US	ENRICO FERMI-1	FBR	1956-08-01	1972-11-29	UD	60
US	FORT ST. VRAIN	HTGR	1968-09-01	1989-08-29	FD	330
US	GE VALLECITOS	BWR	1956-01-01	1963-12-09	SE	24
US	HADDAM NECK	PWR	1964-05-01	1996-12-05	FD	560
US	HALLAM	X	1959-01-01	1964-09-01	ISD	75
US	HUMBOLDT BAY	BWR	1960-11-01	1976-07-02	UD	63
US	INDIAN POINT-1	PWR	1956-05-01	1974-10-31	SE	257
US	LACROSSE	BWR	1963-03-01	1987-04-30	SE	48
US	MAINE YANKEE	PWR	1968-10-01	1997-08-01	FD	860
US	MILLSTONE-1	BWR	1966-05-01	1998-07-01	SE	641
US	PATHFINDER	BWR	1959-01-01	1967-10-01	UD	59
US	PEACH BOTTOM-1	HTGR	1962-02-01	1974-11-01	SE	40
US	PIQUA	X	1960-01-01	1966-01-01	ISD	11
US	RANCHO SECO-1	PWR	1969-04-01	1989-06-07	FD	873
US	SAN ONOFRE-1	PWR	1964-05-01	1992-11-30	UD	436
US	SAXTON	PWR	1960-01-01	1972-05-01	FD	3
US	SHIPPINGPORT	PWR	1954-01-01	1982-10-01	FD	60

TABLE IV–1. DECOMMISSIONING STATUS OF SHUTDOWN POWER REACTORS
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Country	Unit	Type	Const. Date	Shutdown Date	Strategy	MW(e)
US	SHOREHAM	BWR	1972-11-01	1989-05-01	FD	809
US	THREE MILE ISLAND-2	PWR	1969-11-01	1979-03-28	SE	880
US	TROJAN	PWR	1970-02-01	1992-11-09	FD	1095
US	YANKEE NPS	PWR	1957-11-01	1991-10-01	FD	167
US	ZION-1	PWR	1968-12-01	1998-01-01	SE	1040
US	ZION-2	PWR	1968-12-01	1998-01-01	SE	1040

TABLE IV–2. COUNTRIES THAT CURRENTLY HAVE THE CAPABILITY TO DISPOSE OF DECOMMISSIONING WASTE AND (IN PARENTHESES) COUNTRIES AT VARIOUS STAGES OF PLANNING, CONSTRUCTION AND START-UP

EUROPE
(Belgium); Bulgaria; Czech R.; Finland; France; (Germany); Hungary; Latvia: Lithuania; Norway; Poland; Romania; Russian F.; Slovakia; (Slovenia); Spain; Sweden; (Switzerland); Ukraine; United Kingdom
AFRICA
(Egypt); South Africa
AMERICAS
(Argentina); (Brazil); (Canada); (Chile); Mexico; (Peru); United States of America
ASIA and the PACIFIC
(Australia); China; India; (Islamic Republic of Iran); Japan; (Jordan); (Republic of Korea); (Malaysia); (Pakistan); (Philippines)

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Annex V

HUMAN RESOURCES FOR NUCLEAR POWER EXPANSION

V–1. Introduction

The *Nuclear Technology Review 2009* had a short section on human resources for nuclear power. It indicated that there were no good estimates of the human resource requirements associated with the IAEA's high and low growth projections for nuclear power and that data were scarce on the number of trained people and the capacities of relevant programmes around the world. It also stressed that the situation is different in different countries.

Since then, more data have become available, more programmes have been put in place, and there is more information. Over the past several years, the IAEA has worked with universities and other educational and training organizations in Member States to address future workforce demand development and the quality and quantity of education and training programmes to support nuclear power. IAEA activities have focused on curriculums for nuclear education, on networking among universities and on internet platforms for nuclear education. University networks that are supported include the World Nuclear University (WNU), of which the IAEA is a founding supporter, the European Nuclear Education Network Association, the Asian Network for Education in Nuclear Technology and other national and regional initiatives. The IAEA also supports the development of policies and strategies in nuclear education and training. It fosters strong regional and inter-regional nuclear education networks. It facilitates the harmonization of curriculums and promotes the awareness and use of nuclear facilities and simulators to enhance education and training. It also provides consultancy services to address issues related to nuclear education and training.

Several IAEA technical meetings in 2008 and 2009 reviewed the status of nuclear education in over thirty Member States and five educational networks. The IAEA is preparing a technical report on the current status and trends and best practices in nuclear education, which will consolidate information from many different countries.

This additional documentation for the *Nuclear Technology Review 2010* includes selections from different categories of countries, i.e. countries with existing nuclear programmes that are continuing to expand, countries with programmes that have only recently renewed expansion plans, countries with phase-out policies, and countries whose nuclear programmes are growing rapidly.

V–2. Summary information on selected countries

V–2.1. Argentina

Argentina's nuclear power programme developed rapidly in the 1960s and 1970s. Since then, until recently, it has been largely on a plateau. Two nuclear power plants are in operation, providing 6.2% of the country's electricity. Atucha-1 was connected to the grid in 1974 and Embalse in 1983. Construction started on a third reactor, Atucha-2, in 1981. Construction was halted in the 1990s and re-started in 2007. A feasibility study is under way for a fourth reactor intended to start operation around 2015. Argentina is also developing a prototype small (25 MW(e)) pressurized water reactor called CAREM. There are five operational research reactors.

As a result of the number of current projects, the demand in Argentina for qualified nuclear engineers has increased in recent years. However, even during the past two decades of slow global growth in nuclear power, graduates of Argentina's principal nuclear training institute, the Balseiro Institute, never had difficulties securing jobs in the nuclear field. In particular, graduates from the Balseiro Institute played important roles in designing and constructing research reactors for INVAP, an Argentina based company that exported research reactors to Algeria, Egypt, Peru and, recently, Australia. At present, INVAP is the world leader in designing and building research reactors. Graduates of the Balseiro Institute also found employment in the nuclear medicine sector and at the country's uranium enrichment demonstration plant, as well as in non-nuclear fields such as scientific satellites and airport radar systems.

The Balseiro Institute runs three degree programmes — in nuclear engineering, mechanical engineering and physics. It also offers a postgraduate certificate in technological applications of nuclear energy, master's degrees in physics, medical physics and engineering, and PhDs in physics, engineering sciences and nuclear engineering. The Institute takes students from all Latin American countries, most commonly Bolivia, Brazil, Chile, Colombia, Ecuador and Peru. It has special agreements with Argentina's most important technological companies, both nuclear and non-nuclear. Approximately 10% of the Institute's students have fellowships from these companies. In September 2009, the Balseiro Institute became part of the IAEA's network of Collaborating Centres, which helps develop human resources for nuclear technology.

Specific training in metallurgy and materials science started in the Materials Department of the Constituyentes Atomic Centre (CAC) of the National Atomic Energy Commission (CNEA) in 1955. In 1993, this spawned the Sabato Institute through an agreement between CNEA and the San Martín National University (UNSAM) to train students in materials science and technology. This institute was is an efficient mechanism for technology transfer and supplying specialists to institutions and companies involved in research and development or producing high technology products. These include nuclear enterprises like Embalse, Atucha-2, CONUAR, which manufactures nuclear fuel elements, and Fabricación de Aleaciones Especiales, which manufactures zircaloy tubes for fuel elements.

Since 1993, the Sabato Institute has graduated 80 materials engineers, 115 masters of science, 38 PhDs and 20 graduates with certificates in non-destructive testing. About 75% of these graduates are working in Argentina, with the remaining 25% completing studies or working abroad. In Argentina, in addition to the nuclear enterprises mentioned above, many graduates from the Sabato Institute join CNEA research groups on mechanical properties, irradiation damage, hydrogen damage, diffusion, electron microscopy, corrosion, phase transformation, defect theory and continuous mechanics.

A third institute, the Dan Beninson Institute of Technology, was created more recently, in 2006, and offers post-graduate certificates in radiochemistry and nuclear applications, and in nuclear reactors and the fuel cycle.

V–2.2. China

A survey conducted on behalf of the Chinese Commission of Science, Technology and Industry for National Defence during 2004–2005, based on China's 11th National Plan (2006–2010), estimated that approximately 20 400 additional graduates and 'high' professional staff would be needed in the nuclear field (10 000 nuclear technology applications graduates, 8169 nuclear energy industry graduates, and 2235 professionals for nuclear power plant operations, assuming 96 nuclear professionals per 1000 MW(e) unit). This was based on China's plans for 40 GW(e) of new nuclear power on-line by 2020, with a further 18 GW(e) under construction. China therefore estimated (in 2005) that each year 1200 students should graduate in nuclear engineering and technology.

There has also been some consideration of a target of 70 GW(e) of new nuclear power on-line by 2020, with 32 GW(e) under construction. China estimates this would require a 30% increase in industry professional staff (11 030, up from 8169, allowing an additional 5% for retirement and alternative employment) and a doubling of plant operating staff (4500 from 2235). This gives a total of 25 500, 5100 more than for the 40 GW(e) estimate.

From 1998 to 2006 China had only one nuclear specialization for undergraduates, nuclear engineering and technology. However, in 2007, the Ministry of Education added five other undergraduate specializations, nuclear technology, radiation protection and environment engineering, nuclear chemistry and fuel engineering, nuclear reactor engineering, and nuclear physics. There are now 23 universities offering nuclear related specializations for undergraduates.

In 2007, there were 1483 undergraduates enrolled in nuclear courses. In 2008, this rose to 1957, of which 1151 were in nuclear engineering and technology, 219 in nuclear technology, 200 in radiation protection and environment protection, 183 in nuclear chemistry and fuel engineering, 80 in nuclear reactor engineering, and 124 in nuclear physics.

China, like some North American and European countries, faces challenges in attracting students into specialist nuclear power fields. The biggest demand for the industry is in the field of nuclear engineering and technology, where enrolment currently matches demand. However, demand for graduates in nuclear chemistry and the fuel cycle is the hardest to fulfil, mainly because the investment needed to establish the necessary faculties is large and in some universities, due to the difficulty in attracting students, the specialization has been cancelled. This has been identified as a priority area for the next national plan.

In 2009, China held its first National Meeting on Improving Education and Training for Chinese Nuclear Power Industry Personnel, supported by the IAEA. Its objective was to ensure that the different universities complement, rather than compete with, each other in terms of the range of nuclear related specializations offered. This is intended to become a regular event and eventually to include technical schools and industry training centres.

V–2.3. France

As of 1 January 2010, France had 59 operating reactors, one more under construction and produced three quarters of its electricity from nuclear power.

In its continuing use of nuclear power, France faces numerous challenges, including the operation and maintenance of its existing array of reactors, waste management, the decommissioning of obsolete reactors, and research and development for future nuclear systems.

These activities mean that all participants in the French nuclear industry must continually update their approaches and skills, with respect to both domestic and worldwide nuclear power development. This requirement calls for the hiring and training of thousands of scientists and engineers each year in France and its partner or customer countries.

An estimated 40% of the nuclear power staff within Électricité de France (EDF) (more than 4000 engineers and executives in operations, engineering and R&D) will retire within the next ten years. In addition to replacing retirees, EDF will need additional engineers for international projects.

In the past four years, EDF has therefore increased its recruitment levels substantially. In the nuclear field, EDF recruits 500 engineers per year in the different technical domains (operations, design processes, neutron and thermohydraulics physics, civil engineering, structures and materials, chemistry and environment, calculation codes and signal processing, instrumentation and control, etc.). EDF has also developed an internal 'nuclear academy' to train and qualify newly hired staff together with staff recruited from other parts of EDF, which will cover basic knowledge and nuclear culture training and more specialized job training.

AREVA has anticipated the nuclear revival by hiring more than 20 000 new staff members over the past four years, to achieve close to 50 000 nuclear staff in 2010, in line with market forecasts. AREVA also has developed in-house training programmes for new recruits: "The Campus Cycle", for all new managers and engineers, is designed to develop group culture and networks, to develop an understanding of AREVA's businesses, the main technologies and development prospects, and to consolidate the nuclear and occupational safety culture; "The Plants Cycle" is focused on engineers and designed to provide an overview of AREVA's technology and core business and develop a collective working habit.

In order to ensure the availability of necessary human resources, the government established in 2008 the French Council for Education and Training in Nuclear Energy (CFEN) chaired by the High Commissioner for Atomic Energy. It includes representation from the nuclear industry, higher education institutes and research organizations: its mission is to improve the balance between the education options being offered, the number of students and the needs of industry.

Over the next ten years, domestic and international nuclear power activities in France will call for the recruitment of about 13 000 engineers with Master of Science or PhD degrees, and 10 000 science technicians and operators with Bachelor of Science degrees. The chief employers will be EDF, AREVA, GDF SUEZ, national agencies such as the National Agency for Radioactive Waste Management (ANDRA), sub-contractors, R&D agencies such as the French Atomic Energy and Alternative Energies Commission (CEA), and the technical safety organization, Institute for Radiological Protection and Nuclear Safety (IRSN).

In France in recent years about 25 000 students have graduated annually with an engineer's or master's degree. In 2006 about 300 of them graduated in nuclear engineering or a closely related field. This figure will reach 900 by July 2010, a three-fold increase over four years. In addition about 100 students per year obtain a PhD in nuclear energy science. The number of technicians graduating with a nuclear or closely related bachelor of technology currently amounts to about 450 per year.

Accordingly, a number of new nuclear related academic programmes have been opened. Two of them have been designed for international enrolment as they provide their courses in English. One is a new international Master in Nuclear

Energy Science, run by a consortium of several academic institutions (Paris-Sud University, ParisTech, Supélec, École Centrale Paris and the National Institute of Nuclear Science and Technology (INSTN)) with the support of several industrial establishments (EDF, AREVA, GDF SUEZ). This training is aimed at French and non-French graduates holding a good bachelor's degree in the sciences. To foster the international dimension of this programme, the classes are conducted in English. Lasting for two years (around 1000 hours of training), the course will provide the knowledge required to pursue a successful career in the nuclear industry. The curriculum has a number of different modules: a foundation course in nuclear sciences, applied knowledge (e.g. safety and radiation protection) focusing on the nuclear industry, and a wide choice of specializations: engineering, design, operations, decommissioning and waste management, and the fuel cycle. An internship in the industry and the submission of a master's thesis to secure the degree will complete the programme. The whole programme became fully operational in September 2009 (90 students, more than 50% non-French coming from 19 countries).

The second programme is an international Master of Materials Science for nuclear energy at the Grenoble Institute of Technology, in partnership with EDF, INSTN, and McMaster University in Canada.

The nuclear industry also set up new education and training programmes. For example, AREVA is involved in the creation of the European Nuclear Energy Leadership Academy. Its Corporate University has a network of correspondents and collaborators in Germany (e.g. Munich University of Technology and Karlsruhe Institute of Technology), North America (e.g. Massachusetts Institute of Technology, Stanford University and Harvard University), South Africa (North-West University), Latin America, China and India.

Finally, France has also played a leading role in the launch, by the European Nuclear Education Network (ENEN) Association, of the European Master of Science in Nuclear Engineering (EMSNE), with participating universities in most EU member countries.

V–2.4. Germany[42]

There are currently 17 reactors operating in Germany. In 2008, they produced 29% of Germany's electricity. The future prospects for nuclear power in Germany are in flux. In 2002, the Bundestag voted to phase out nuclear power, allowing an average lifetime of about 32 years for each operating reactor, but with the provision that kilowatt-hours could be traded between reactors. Based on

[42] This section borrows heavily from Ref. [V–2].

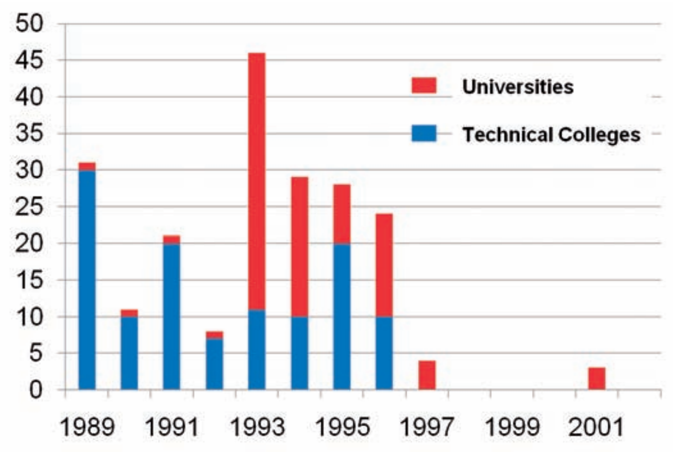

FIG. V–1. Graduates in nuclear technology in Germany [V–3].

recent planning, the remaining reactors would have to be shutdown between 2010 and 2022 (although the provision for trading kilowatt-hours makes it impossible to project precise shutdown dates). The new government elected in September 2009 has stated its commitment to rescind the phase-out policy and reconsider nuclear power as a 'bridging technology'. At the time of writing, the possibility of rescinding the phase-out policy was still under discussion.

Partly as a result of the phase-out policy, there have been declines in the numbers of students and educational programmes in nuclear fields. A 2004 analysis of nuclear education concluded that the number of academic institutions teaching nuclear related matters was expected to decline from 22 in 2000 to 10 in 2005 and only five in 2010 [V–4][43]. As shown in Fig. V–1, the number of graduates receiving diplomas in nuclear technology dropped from 46 in 1993 to zero in 1998. From 1998 through 2002, only two students graduated in a nuclear technology.

In order to try to combat this decline, the Alliance for Competence in Nuclear Technology (Kompetenzverbund Kerntechnik) was created in 2000, representing nuclear research centres, universities, technical support organizations and federal ministries. In 2009, the Karlsruhe Institute of Technology also established the AREVA Nuclear Professional School, which enrols 30 PhD students at a time, who are paid by AREVA and guaranteed a job when their training is completed [V–5].

[43] Updated data are not available to check whether these forecasts have been realized.

V–2.5. Hungary

Hungary operates four reactors at the Paks nuclear power plant, which provide 37% of the country's electricity. In 2008, the thermal power of Paks was uprated by 8%, and the plant submitted a preliminary plan to extend the operation of its reactors beyond their original retirement dates of 2012–2017. In March 2009, Hungary's parliament approved a decision in principle to construct two new reactors at Paks.

Hungary therefore needs new nuclear experts to replace retiring personnel in nuclear related organizations; to serve as new personnel to allow for the extension of the lifetimes of the existing Paks reactors; and to serve as new personnel to construct and operate the new reactors.

In 2006, the Hungarian Atomic Energy Authority conducted a survey to assess future workforce needs in the energy sector. It did not assess specific needs for nuclear power, but it included responses from five nuclear organizations which can be analysed separately. Overall, only 23 companies completed the survey, and it is estimated that real energy sector needs may therefore be twice or three times the estimates collected in the survey.

Of 16 707 people employed by the respondents, 3881 had completed higher education in scientific and technical subjects. The age distribution of these employees is shown in Fig. V–2. It is very close to, indeed a little younger than, the age distribution for a hypothetical stable workforce in which all employees start working at 25 and retire at 60 [V–6].

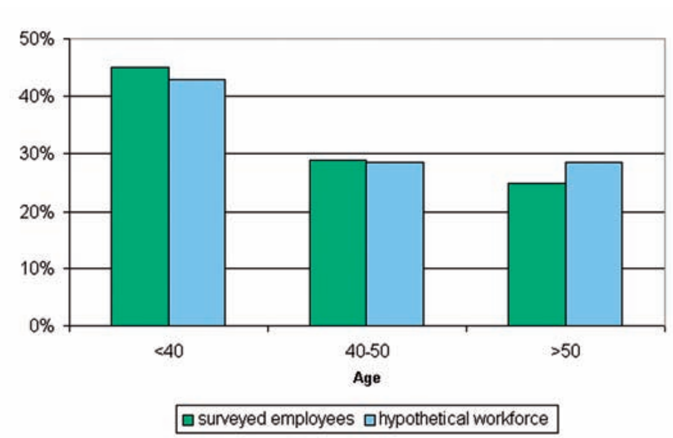

FIG. V–2. Age distribution of surveyed employees with higher education in science or technology (dark green) and a hypothetical stable workforce in which all employees work from 25 to 60 (light blue).

For the five nuclear organizations that were surveyed, Table V–1 shows the percentage of employees who are due to retire within ten years. In the hypothetical workforce described above the percentage would be 29%. Thus four of the five nuclear organizations have larger retirement cohorts than those of a hypothetical workforce, and the Paks nuclear power plant, at 44%, has the largest percentage of all.

The results for all 23 survey respondents estimated a need, over the next ten years, for approximately 1120 new employees with higher education in science or technology. A little more than half would need Bachelor of Science degrees. The rest would need Master of Science degrees. Again, because of the limited survey response, the real need might be twice or three times as much.

The decision in principle for new units at Paks came after the survey, so workforce needs for the new reactors were not included in the responses. Separate estimates of workforce needs for two new units at Paks have, however, been made [V–7]. During the construction period, a direct work effort estimated at 11 000–13 500 person-years would be needed, plus an indirect workforce of about 16 500–20 300 person-years. The indirect workforce includes those not directly involved in the construction, but who deliver components, for example, or are otherwise indirectly involved.

After construction, an estimated 700–800 people would be needed for everyday operations and maintenance, about 30% of whom would need higher education. The new reactors will create additional work for the Hungarian Atomic Energy Authority and technical service organizations (TSOs), but it is difficult to estimate how much, particularly before the technology has been chosen.

Five universities in Hungary offer nuclear related courses. The Budapest University of Technology and Economics (BME) has the largest number of graduates with nuclear related degrees. In addition, the Paks nuclear power plant has its own education and training centre. This centre has a full-scale simulator

TABLE V–1. PERCENTAGE OF EMPLOYEES WITH HIGHER EDUCATION IN SCIENCE OR TECHNOLOGY WHO ARE DUE TO RETIRE WITHIN TEN YEARS

Paks nuclear power plant	44%
Research Institute for Electric Industry (VEIKI), Division of Nuclear Power	42%
Hungarian Atomic Energy Authority	39%
Radioactive Waste Treatment Ltd	31%
Budapest Research Reactor	23%

for operator training and a maintenance training centre for technicians and maintenance workers.

All five universities cooperate with the nuclear industry. The broadest cooperation is between BME and Paks. BME offers a continuing education programme for professionals and serves as a TSO for Paks. Paks funds a foundation for BME to, among other things, promote student mobility, provide special scholarships, cover student travel expenses for conferences, and award scholarships and prizes recognizing exceptional work.

V–2.6. India

India plans a rapid expansion of nuclear power. At the end of 2009, it had 18 reactors in operation (3984 MW(e)) and 5 under construction. Projections made in 2004 included 29.5 GW(e) of installed nuclear power in 2022 [V–8], and higher numbers have been cited more recently: Indian Prime Minister Manmohan Singh, in opening the International Conference on Peaceful Uses of Atomic Energy in New Delhi in September 2009, said India could potentially install 470 GW(e) by 2050. Estimates based on adding 20 GW(e) of nuclear capacity by 2020 indicate that by 2017 India would need to add 3700 nuclear engineers, compared to an estimated 3180 today [V–9].

To support its expansion plans, the Indian Department of Atomic Energy (DAE) has established a number of new institutes and educational programmes to augment its ongoing, well established nuclear training programmes (i.e. the one year orientation course for engineering graduates and science postgraduates and the two year DAE graduate fellowship scheme), mainly at the Master’s degree and PhD level, including:

- The Homi Bhabha National Institute in 2005, an umbrella for ten existing R&D and education institutions;
- The National Institute of Science Education and Research in 2007;
- The Centre for Basic Sciences at the University of Mumbai in 2007.

The Nuclear Power Corporation of India Limited (NPCIL), the country’s sole constructor and operator of nuclear power plants, also has its own nuclear training centres close to nuclear power plant sites. The majority of training for non-graduate technical staff as well as for new engineering graduates and other technical staff is provided through these centres.

More recently, some Indian universities too have begun courses in nuclear engineering, e.g. in 2008, the Jawaharlal Nehru Technological University started a two year Master’s course in nuclear engineering for candidates holding engineering degrees in mechanical, chemical, civil or metallurgy fields.

V–2.7. Japan

Japan is the world's third largest producer of electricity from nuclear energy. It has plans both to further expand production and to expand its exports of nuclear related products and services.

The Nuclear Energy Human Resource Development Council of Japan is responsible for the medium and long term development of human resources for the Japanese nuclear industry. In April 2009, it published a report entitled *Efforts for Nuclear Energy Human Resource Development* [V–10], based on interviews and surveys of industry, educational and research institutions, students and new employees.

Around 700–800 students major in nuclear subjects at the graduate level every year: 200–300 of those go on to further education, and some 500 find employment. About 40% of the 500 (i.e. 200) are employed by nuclear industry. Utility companies employ around 100 graduates every year, about 20% of whom majored in nuclear or related subjects. Manufacturers employ around 100–150 graduates every year, about 10% of whom majored in nuclear or related subjects. The report expressed no immediate concerns about the number of new graduates Japan was producing, but the survey gave rise to concerns about the quality of the graduates, particularly because the quality of education on nuclear subjects was seen to be weakening. Figure V–3 indicates that the total number of nuclear related subjects in nuclear related university departments was reduced by half between 1979 and 2007. In the area of nuclear reactor physics, the number fell by two thirds. In the area of experiments and practical training, the number fell by 80%.

The following actions have been adopted as a result of the survey findings:

For government:

— To implement nuclear human resources development programmes and continue to support activities in education; and
— To support energy and environment education at elementary and junior and senior high schools.

For universities:

— To ensure that education incorporates industry needs;
— To ensure, through strict management of educational curricula, the quality of master course students;
— To develop young researchers in the area of basic engineering and technology.

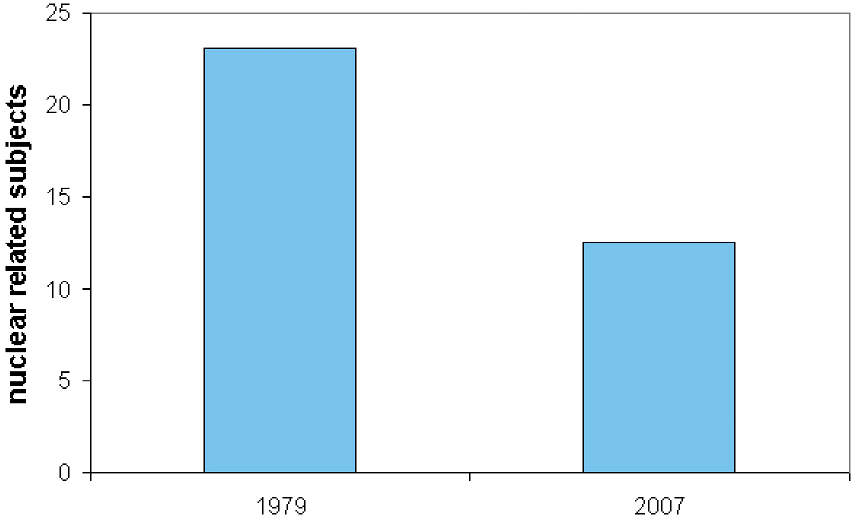

FIG. V–3. Total number of nuclear related subjects in nuclear related university departments in Japan.

For industry:

- — To develop human resources through on-the-job training;
- — To promote self-development by providing incentives for additional qualifications;
- — To cooperate with and support schools and universities.

V–2.8. United Kingdom

The UK nuclear energy industry currently has just over 10 GW(e) of installed capacity and employs 44 000 people (24 000 core nuclear staff and approximately 20 000 contractors) of which 7500 are employed directly in electricity generation.

In 2009, a national survey was conducted by Cogent[44] [V–11] to address a lack of data to support long term skills planning. The survey identified three important skills drivers for the immediate future:

[44] Cogent is the Sector Skills Council (SSC) for the Chemicals and Pharmaceuticals, Oil and Gas, Nuclear, Petroleum and Polymer Industries. It is licensed by the UK Government to provide employers in the sector with the opportunity for coherent leadership and strategic action to meet their skills needs.

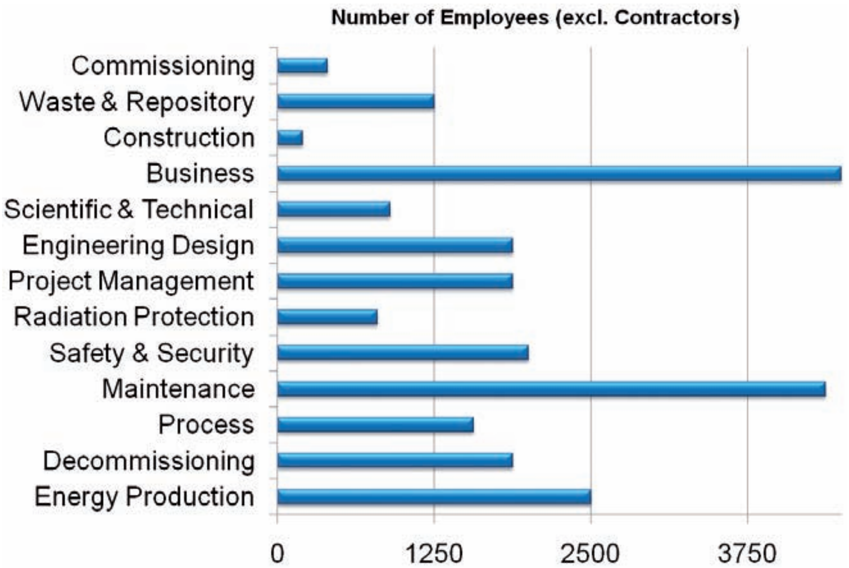

FIG. V–4. Job contexts for core nuclear industry staff.

— An ageing workforce driving a demand for replacement skills;
— A shift in needed skills toward decommissioning;
— New demand for skills to operate a fleet of new nuclear power stations.

If no new nuclear power reactors are built, and if current reactors are retired on schedule, the total workforce is estimated to decline by 58% by 2025. This in fact is the model that has driven workforce planning in the UK in recent years. However, subsequent to a 2008 Government energy review [V–12], the private sector announced intentions to build at least 12 GW(e) of new nuclear power capacity. This would create 4600 new jobs in generation alone.

These jobs would require diverse skills as shown in Fig. V–4. One of the largest categories is maintenance, where the majority of staff would not be university graduates, but vocationally qualified technicians.

However, over the past 20 years, the UK has seen a dramatic reduction in the availability of traditional engineering apprenticeships, which would have been the ‘feedstock’ for maintenance and similar jobs. The National Skills Academy for Nuclear was established in 2008, at the request of nuclear industry employers, to address the key skills and training challenges facing the industry, but it is still too early to say whether it will be successful in meeting the needs of the industry.

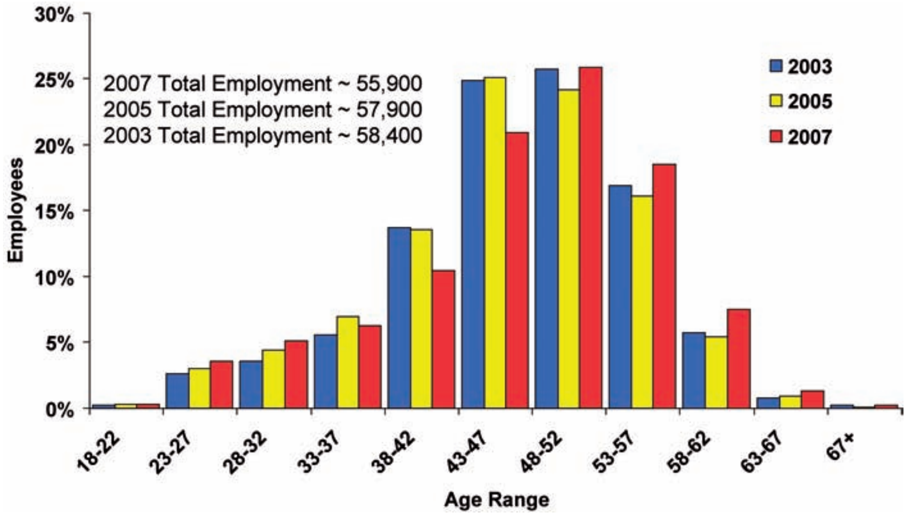

FIG. V–5. Age profiles of the workforce in the US nuclear power industry.

A number of UK universities have also joined the European Nuclear Education Network (ENEN) Association, which, as noted earlier, launched a European Master's degree in nuclear engineering in 2005 to help alleviate the predicted shortage of professional staff.

V–2.9. United States of America

The ageing workforce is also a key driver of recruitment needs in the USA. The Nuclear Energy Institute (NEI) biennially conducts a workforce analysis for the US nuclear power industry. Its 2009 survey is in progress. Its 2007 survey, for which 20 out of 26 utilities supplied data (representing 85% of utility employees), indicated that the age profile of the workforce has become older (see Fig. V–5):

- In engineering only 13% of employees were under 33 years old (compared to an expected value of 25% for a hypothetical stable work force of 22- to 62-year olds);
- In operations only 14% of employees were under 33 years old;
- In maintenance only 6% of employees were under 33 years old;
- In radiation protection only 4% of employees were under 33 years old.

The survey also found that, for skilled trades, there were indications of increased shortages in welders, ironworkers and pipefitters.

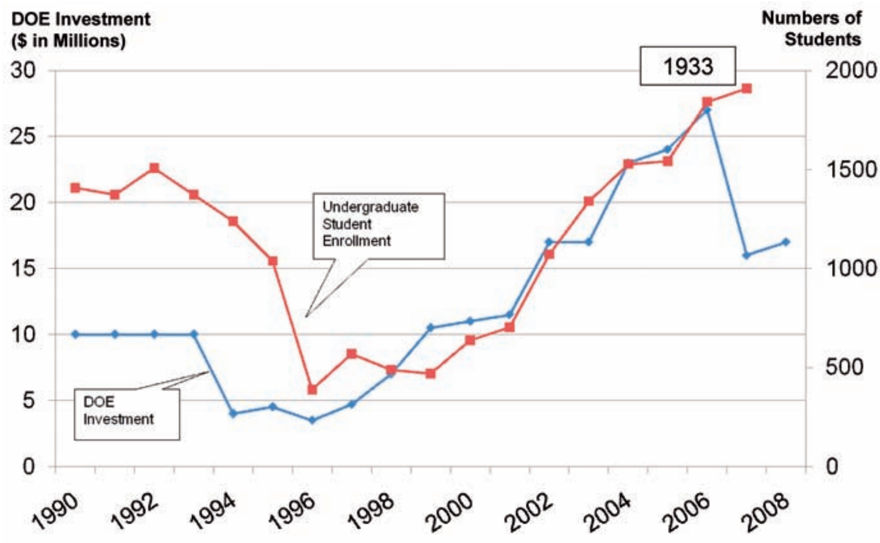

FIG. V–6. Undergraduate enrolments in nuclear engineering and DOE investments in university programmes.

Many of the recent studies in the USA focus on university education. Funding for university nuclear science and engineering education relies heavily on government support, historically from the Department of Energy (DOE) and currently from the Nuclear Regulatory Commission (NRC). After the Three Mile Island and Chernobyl accidents, as the construction of new plants ceased, student enrolments in nuclear engineering programmes declined and DOE funding was steadily reduced. By the mid 1990s, anticipating a possible resurgence in nuclear energy, the DOE began reinvesting to rebuild the nuclear energy education infrastructure. The results of this reinvestment, in terms of increased student numbers can be seen in Fig. V–6 [V–13].

Approximately 450 Bachelor's degrees were granted in nuclear engineering in 2008, of which an estimated 60% continued with further education and 25% were hired by vendors and regulators, meaning that fewer than 100 were available to be hired by utilities. This is well short of utility estimates according to which approximately 500 new graduate recruits will be needed each year just to cover retirements and attrition. Building new nuclear power plants will require even more new recruits [V–14].

In those areas where government or other support has not been forthcoming, the situation is worse. Figure V–7 highlights the decline in the number of PhDs awarded annually in nuclear chemistry. This is a very specialized area, but one which is fundamental for research and development.

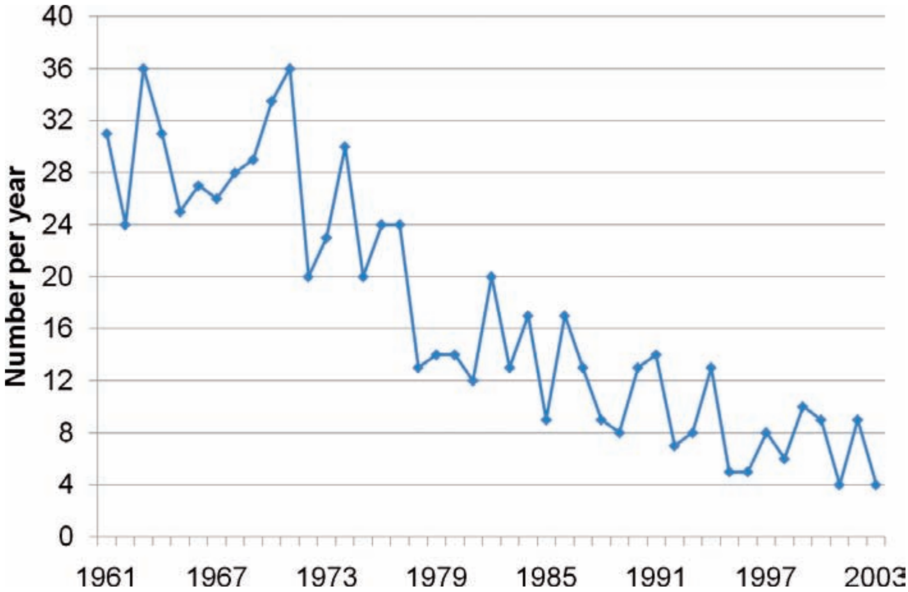

FIG. V–7. PhDs awarded annually in nuclear chemistry in the USA [V–14].

The USA has had some success with partnering and outreach programmes, particularly in the area of associate's degrees, which are two year degrees for skilled workers. In these programmes, utilities work with local educational institutions to develop programmes targeted at meeting the utilities' needs. Figure V–8 indicates that, typically for the USA, staff with associate's degrees make up around 70% of the workforce. An example of such a programme is the Nuclear Power Institute (NPI), a partnership between Texas A&M University, three US nuclear utilities and several other four year universities and two year community colleges. NPI is developing curriculums to meet the full breadth of utility needs and has a significant outreach programme to engage high schools, teachers and students and attract students to nuclear power programmes.

V–3. Concluding remarks

As noted at the outset, the basic conclusions on human resources for nuclear power have not changed from the *Nuclear Technology Review 2009*. The concerns about possible shortages of qualified people remain although the situation is different in different countries. For countries with expanding nuclear power programmes the challenge is to scale up existing education and training in order to have the required qualified workforce on time. Countries planning to supply nuclear technology to others not only have to meet their national human

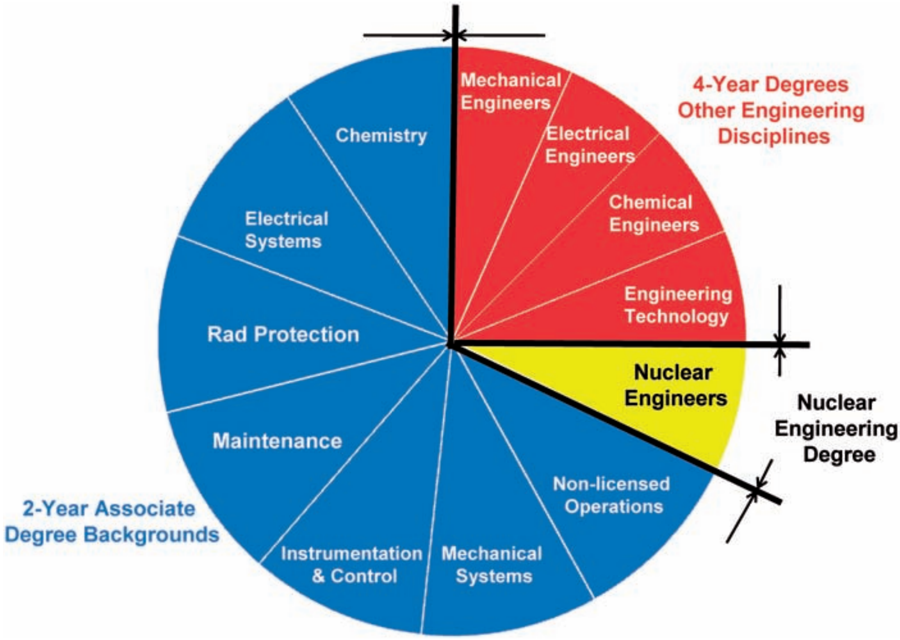

FIG. V–8. Example of distribution of disciplines for the nuclear workforce.

resource needs but must also be able to transfer education and training capacity together with the technology they transfer. Countries embarking on nuclear power will need to rely significantly on their technology supplier to help provide qualified people for construction, licensing and start-up until their national capacities to train comparable workforces domestically are established.

Assembling and analysing the data for more comprehensive conclusions on global human resources for nuclear power will require an international effort. With cooperation from the OECD/NEA, the World Association of Nuclear Operators, the World Nuclear Association, the Nuclear Energy Institute and Los Alamos National Laboratory in the USA, the Japan Atomic Energy Agency, the Cogent Sector Skills Council in the UK and others, the IAEA announced the launch of such an effort at the International Conference on Human Resource Development for Introducing and Expanding Nuclear Power Programmes, in March 2010 in Abu Dhabi. 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.

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Annex VI

RISING EXPECTATIONS FOR NEW NUCLEAR POWER PROGRAMMES

VI–1. Overview

In recent years, in every region of the world, many countries have expressed a new or renewed interest in nuclear power. In the context of growing energy demands to fuel economic growth and development, climate change concerns, and volatile fossil fuel prices, as well as improved safety and performance records, some 60 countries are expressing interest in, considering, or actively planning for nuclear power. This comes after a gap of nearly 15 years, during which international markets, energy systems and strategic concerns have evolved. Countries introducing nuclear power now face different conditions than in the past, and are responding to them in new and creative ways. This annex explores these issues, with a specific focus on countries planning for a first nuclear power plant. However, countries planning expansion of existing nuclear power programmes, some of which have not built new reactors for more than a decade, may also share some of these issues.

IAEA projections reflect the interest being expressed. The latest low and high projections, from 2009, indicate a global increase in installed nuclear generation capacity, by 2030, of between 35% and 120%. Most of that new capacity will be built in countries that already have operating nuclear power plants. But the projections also include between about 10 and 25 countries that will commission their first nuclear power plants by 2030. That is an increase from projections in 2008. It is important to note that Agency projections are not predictions. Additional information about how the projections are developed and their track record against historical data is presented in *International Status and Prospects of Nuclear Power* [VI–1].

Another indicator of increased interest is the three-fold increase in the number of IAEA technical cooperation projects related to nuclear power (Fig. VI–1). There were 13 in the 2007–2008 cycle, and there are 35 in the current cycle, 2009–2011. As of 2009, 58 countries were participating in national and/or regional projects related to the introduction of nuclear power through the Agency's technical cooperation programme.

Table VI–1 shows the numbers of countries at different stages of nuclear power consideration or development. Sometimes referred to as 'nuclear newcomers', some countries, such as Bangladesh, Egypt and Vietnam have in

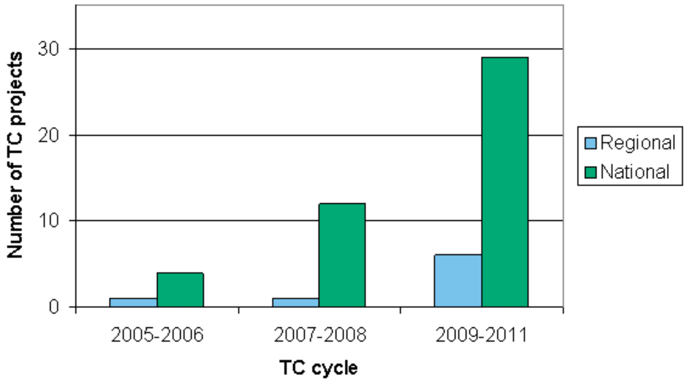

FIG. VI–1. The numbers of regional and national technical cooperation (TC) projects related to nuclear power in the three most recent TC cycles.

TABLE VI–1. STATUS OF COUNTRIES PLANNING FOR A FIRST NUCLEAR POWER PLANT

Interested in nuclear power, but have not started planning to introduce nuclear power	23
Considering nuclear power with a strong indication of intention to proceed	17
Have included nuclear power as an option in their energy mixes and are actively preparing nuclear power programmes	17
Have invited bids from suppliers of nuclear power plants[a]	2
Constructing a first nuclear power plant	1

[a] The United Arab Emirates selected a bid at the end of 2009. Turkey cancelled its bidding process in 2009.

fact been planning for nuclear power for some time. Others, such as Poland, are reviving the nuclear power option after plans had been curtailed when Governments and public opinion changed. Countries such as Jordan, Mongolia and Uruguay are considering nuclear power for the first time. What they all have in common is that they are considering, planning or starting nuclear power programmes, and have not connected a first nuclear power plant to the grid.

The Islamic Republic of Iran, which has announced plans to complete commissioning of the nuclear power plant at Bushehr soon, is likely to be the next country to connect its first nuclear power plant to the grid.

The rate at which the 32 countries that currently use, or have used, nuclear power connected their first nuclear power plants to the grid was fairly steady

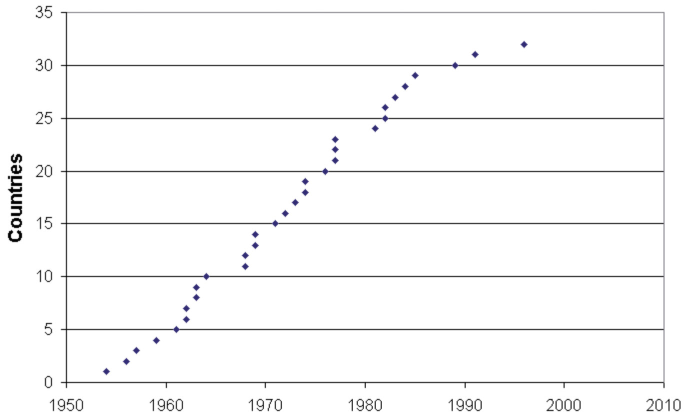

FIG. VI–2. Cumulative number of countries having connected a nuclear power plant to the grid by the year shown on the horizontal axis.

through the early 1980s (Fig. VI–2). Only three countries connected their first nuclear power plants to the grid in the post Chernobyl era — China, Mexico and Romania. The countries now planning for their first nuclear power plants are doing so after an experience gap of fifteen years.

The international context in which the current 'newcomers' are planning programmes is different than in the past. The Chernobyl accident in 1986 had a major impact on public opinion regarding the use of civil nuclear power. In the aftermath, an expectation for transparency and openness regarding the nuclear power industry and nuclear safety was captured in the Convention on Nuclear Safety, which entered into force in 1996, and the subsequent Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, which entered into force in 2001.

Challenges to the non-proliferation regime associated with the discovery of clandestine programmes may also affect the introduction of nuclear power. International efforts to strengthen the non-proliferation regime and greater emphasis on nuclear security and control of nuclear material are important tools to mitigate possible negative impacts.

New construction starts on nuclear power reactors had, in fact, already been in decline prior to the events of the 1980s and 1990s, largely due to economic factors and the availability of alternatives in the energy sector. The number of reactors under construction peaked in 1979 at 235 after which began a precipitous decline (Fig. VI–3). A global recession in the late 1970s and government debt defaults in some developing countries in the early 1980s led to a decline in energy

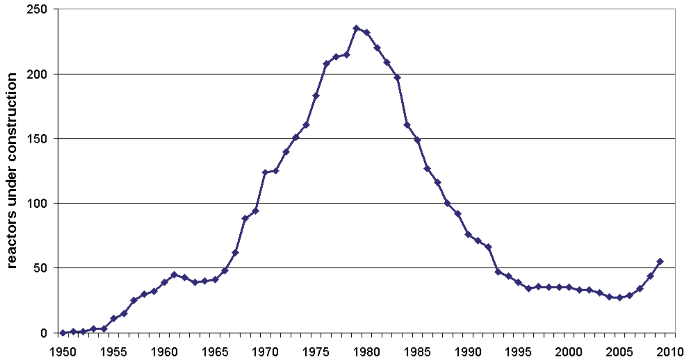

FIG. VI–3. Number of reactors under construction at the end of every year since 1950.

demand. At the same time, the expanded use of natural gas, hydropower and other renewables were all being explored.

Concerns about climate change have affected perceptions regarding the use of coal and other fossil fuels for electricity production. Some prominent environmentalists are now publicly supporting nuclear power. Policy discussions on climate change are inexorably linked to energy for sustainable development. Some who held the view that nuclear power could not contribute to sustainable development are now reconsidering nuclear power as an important contributor to meeting carbon emission limits and fuelling development [VI–2].

Some developing countries are running out of options. Chile, for example, has developed much of its hydropower potential. It recently experienced a ‘perfect storm’ of circumstances when a major drought reduced output from hydropower at the same time that imports of natural gas were disrupted, and it has begun to study the viability of the nuclear power option. Bangladesh expects to use up its stores of natural gas within the coming decade and has few options to meet its baseload energy production.

Of the countries actively planning for nuclear power, 24 have one or more research reactors. However, nuclear power can be implemented without first having a research reactor — for example, the United Arab Emirates is taking this approach — but the national experience with nuclear materials provided by a research reactor can also provide the basis for understanding the technical and legal requirements associated with operating nuclear facilities, and thus contribute to the infrastructure necessary for nuclear power. Indeed, because the IAEA’s guidance in *Milestones in the Development of a National Infrastructure for Nuclear Power* (IAEA Nuclear Energy Series NG-G-3.1) was developed for countries with little or no nuclear experience, some countries with research reactors have found, through self-assessments, that because of their experience with research reactors and other nuclear facilities, they are able to meet the conditions for some of the 19 issues for the first phase identified in the publication.

VI–2. Common issues and examples from specific countries

VI–2.1. Public opinion and public acceptance

Issues and trends in the public acceptance of nuclear power were discussed briefly in the *Nuclear Technology Review 2009*. Newcomers are facing issues of public acceptance similar to those faced by countries that are expanding existing nuclear power programmes. The general optimism in the 1960s regarding science and technology's contributions to solving the world's problems, eliminating poverty, and providing security has shifted to include more scepticism regarding science as a problem solver. Technology is often associated with negative impacts (on the environment, for example) as well as positive ones. Sustainable development is sometimes equated with small scale, community based development, microloans, and low tech solutions on a limited scope at the expense of large scale investments, such as would be required for nuclear power. With a few notable exceptions, countries reviving or starting nuclear programmes are, in general, educating the public and providing unbiased information regarding the nuclear power option.

Chile is engaging its public in the consideration of nuclear power as an option. In 2007, when then President Bachelet decided to launch a study group to consider nuclear power, she announced that the process would be transparent to the public. She brought together a group of eminent national experts who produced a report concluding that Chile could not afford to exclude the possibility of nuclear power. This resulted in further study of the nuclear power option in the country, led by a newly appointed Minister of Energy, with special emphasis on public information. Opinion leaders and the general public were invited to a series of public seminars on nuclear power.

VI–2.2. Sustaining support

Historical experience shows that the planning process for starting a nuclear power programme usually takes between 10 and 20 years, or sometimes longer. Society generally must be able to maintain support for the planning process through changes in political leadership. Once a country makes a large scale investment, especially once the contract is issued and construction begins, it is easier to maintain momentum through reactor commissioning and operation. However, in the period prior to the issuance of the contract the unrecoverable costs are related to planning and are relatively limited. Building broad government and public support for a nuclear power programme is one way of sustaining the planning process.

VI–2.3. New approaches to contracting nuclear power plants: Build–own–operate

Traditionally, nuclear power plants and other large scale investment projects have required government involvement, including financial guarantees. A wave of sovereign debt defaults in the early 1980s resulted in new difficulties with governments taking on such financial risk. Around that time, a new approach to financing large scale infrastructure projects was initiated in which government backed utilities offered a guaranteed price for electricity, which could be used by the technology suppliers to secure commercial financing. According to this approach, the power plant supplier would establish a project company that would build, own, and operate the plant for a fixed period of time, without putting its other financial assets at risk. This non-recourse financing has not been used for nuclear power plants, although it has become common in other parts of the energy sector. Experts are sceptical about whether investors would be willing to accept this approach without some direct government financing because of the economic risks associated with the project.

Some countries have expressed renewed interest in applying non-recourse financing to nuclear new construction for two additional reasons. First, in a country with little existing nuclear infrastructure, a consortium including an operator could bring to a new plant experience with plant operations, management systems and training for some period of time, allowing local staff to learn alongside experienced personnel. Second, the supplier consortium, which would have a track record in the nuclear industry, and would take responsibility for securing financing at perhaps more favourable rates than a new operating organization would be able to get.

The United Arab Emirates accepted a bid from a consortium led by the Korea Electric Power Corporation at the end of 2009 which may have elements of this approach, although the details of the bid specifications have not been made public, and negotiations are ongoing.

Jordan has also indicated an interest in using a build–own–operate approach, as it plans for a national nuclear power programme. In addition to bridging the experience gap, Jordan has indicated that it is interested in supplier-secured financing.

VI–2.4. Regional approaches

One way that countries are exploring reducing the national investment in the infrastructure necessary for nuclear power, and at the same time securing access to electricity, is through regional approaches to nuclear power development. The concept is that the nuclear power plant would be located in one country, under that country's national legislation and regulation, with shared responsibility for financing and other aspects of the plant operations, in exchange for guaranteed shares of the electricity produced by the plant. A regional approach differs from cross-border investment and operation of reactors by utility companies (as happens in many instances in Europe) by the level of responsibility for operations and waste assumed by the co-investors and by the backing of government to government agreements specifying responsibilities. One prerequisite for a regional approach would be cross-border interconnections of the electrical grid allowing the output of a nuclear power plant to benefit the partners. Negotiations on who hosts the nuclear power plant, the level of investment and responsibility of the partners, and the shares of benefits and liabilities to be assumed by the partners can be challenging and time-consuming. The Krško plant is an example of a nuclear power plant being co-owned, in this case by Slovenia and Croatia.

The countries of the Cooperation Council for the Arab States of the Gulf (GCC — Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the UAE) have expressed interest in a regional approach and are working with the IAEA through a regional technical cooperation project to understand the issues associated with nuclear power.

In July 2006, Lithuania invited Poland to join Estonia and Latvia in a regional approach for the implementation of a replacement for units being shut down at the Ignalina site in Lithuania. Lithuania, Estonia, Latvia and Poland have indicated their intentions at the government level, and the partners established a project development company, Visaginas. Final agreement regarding the levels of investment and electricity off-take among the partners has not yet been reached. One precondition for a regionally owned nuclear power plant is in place — the Baltic States have an interconnected grid, although a connection to Poland would need to be developed.

VI–3. International cooperation and coordination

There is a sense of shared responsibility for assisting newcomers in developing safe, secure and effective nuclear power programmes that do not contribute to the risk of nuclear proliferation. Several countries that have operating nuclear power programmes or supply nuclear technology have launched national and international cooperative and coordinating efforts.

One example of an international effort is the Global Nuclear Energy Partnership (GNEP), launched by the United States of America in 2006, which now has 25 partner and 31 observer countries. GNEP (which is considering changing its name) currently has two working groups, one on reliable fuel services and another on infrastructure development. The Infrastructure Development Working Group assists participating countries in the development of the infrastructure needed for the expansion of nuclear energy in a safe and secure manner by identifying common interests and concerns, supporting information sharing and recommending practical measures. The Reliable Fuel Services Working Group carries out work towards the establishment of international frameworks, which may ensure reliable, cost effective fuel services and supplies for generating nuclear energy and fostering development by creating viable alternatives to the acquisition of sensitive fuel cycle technologies. The working groups are overseen by a steering committee and an executive committee at the ministerial level.

Several efforts are also under way for national government to government cooperation. In 2008, France launched the France International Nuclear Agency (AFNI), under the Atomic Energy Commission (CEA), to provide assistance to countries launching nuclear power programmes. In November 2009, France and Poland inaugurated a training programme to assist Poland in the development of its national nuclear power programme.

In light of the number of international initiatives and bilateral cooperative arrangements currently ongoing and being developed, several Member States have asked the IAEA to consider how to improve coordination among these efforts. The IAEA identified three levels of coordination:

- *Issue specific coordination.* For example, countries providing training and support for safeguards implementation are coordinating their activities to improve delivery of assistance to countries introducing nuclear power.
- *Country specific coordination.* For example, if a country is receiving support from multiple countries and the IAEA, it may wish to improve coordination among its assistance providers to improve efficiency.
- *International coordination*. The international community also benefits from having workshops to identify common challenges that countries are facing in order to focus on the development of new approaches.

VI–4. Regulators

Developing competent regulators to oversee new nuclear power programmes is an issue that has been gaining attention in the international nuclear safety community. It has been raised in recent years in the Senior Regulators Meeting, the International Nuclear Safety Group (INSAG), and the G8 Nuclear Safety and Security Group. The regulatory body needs to establish the regulatory framework and develop the licensing process in advance of the bidding process. Although the owner–operator organization in a newcomer country has access to training and experienced personnel through the contract, the regulatory body may not have the same contractual arrangement. The regulatory body could benefit from the experience of well established regulatory bodies that have licensed similar facilities. Experienced regulators are discussing how to coordinate support, training, and assistance for countries introducing nuclear power.

VI–5. Agency assistance on planning and building nuclear power infrastructure

If expectations of a surge in introducing nuclear power materialize, several questions arise. How will newcomer countries develop human resources to operate nuclear power plants? How do they build the appropriate nuclear power infrastructure to support the first nuclear power plant? How will emerging nuclear power countries build the relevant national trust and international confidence in their nuclear power programmes?

In this context, countries considering the introduction of nuclear power are increasingly seeking the support of the IAEA. The IAEA’s assistance is intended to encourage emerging nuclear power States to build a solid infrastructure and make the best use of available technology, with high levels of safety, security and non-proliferation. As noted earlier, the IAEA published *Milestones in the Development of a National Infrastructure for Nuclear Power*, identifying a phased approach for the progressive development of infrastructure and outlining 19 infrastructure issues to be addressed in each phase. The IAEA supports Member States in each of these three phases through technical assistance provided through the technical cooperation programme and development of publications and guidance documents.

The IAEA’s assistance is designed to help Member States in their work to plan properly, to build the nuclear power infrastructure, to establish independent and effective regulators, and to adhere to international safety, security and non-proliferation instruments.

Several Members States are in the first phase described in *Milestones in the Development of a National Infrastructure for Nuclear Power* and are developing national strategies. IAEA assistance is available for these States to aid them in developing an understanding of the issues needed to make an informed commitment to nuclear power.

A competent workforce plays a key role in building required infrastructure and regulating and operating nuclear power installations. IAEA assistance is available to newcomer States for establishing policies for training and workforce planning. Support is also provided for assessing the national education system to develop appropriate programmes to support the nuclear power programme. The IAEA published *Managing Human Resources in the Field of Nuclear Energy* (IAEA Nuclear Energy Series NG-G-2.1) in 2009 and is preparing a publication on workforce planning in the field of nuclear energy.

One important aspect of the IAEA's milestones approach is self-evaluation of infrastructure development, which can help a Member State establish its priorities, target its resources, and make the best use of international cooperation. The IAEA also offers Integrated Nuclear Infrastructure Review (INIR) missions, which are external expert reviews of Member State infrastructure development according to the milestones approach. Self-evaluation and external reviews, which cover both the 'hard' infrastructure (grid, facilities, etc.) and 'soft' infrastructure (legal, regulatory, training, etc.), reinforce continual improvement in the planning process, identify gaps, focus resources, and build confidence in a country's infrastructure development. INIR missions took place in 2009 to Jordan, Indonesia and Vietnam. Five INIR missions are expected in 2010.

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Annex VII

PRODUCTION AND SUPPLY OF MOLYBDENUM-99[45]

VII–1. Background

Over 80% of diagnostic nuclear medical imaging uses radiopharmaceuticals containing technetium-99m (^{99m}Tc), entailing over 30 million investigations per year. The excellent nuclear characteristics of ^{99m}Tc enable high quality images with low radiation doses to patients. Its chemical characteristics make it very versatile for attaching to different chemical substances, so that it can be used to target different organs and diseases as required by different diagnostic procedures. The two most widely used ^{99m}Tc based procedures are for imaging blood flow to heart muscles (myocardial perfusion imaging) and mapping the spread of cancer to bones (skeletal metastases imaging). The medical use of ^{99m}Tc has grown significantly in the past several decades, and moderate overall growth of 3–5% per year is expected to continue, with particular growth in countries expanding health care programmes. The IAEA is particularly active in helping developing countries to expand their use of ^{99m}Tc based imaging procedures.

With a half-life of only six hours, ^{99m}Tc must be produced near the place and time it is to be used. It is produced by the decay of molybdenum-99 (^{99}Mo), which has a half-life of 66 hours. Production is carried out with a ^{99}Mo–^{99m}Tc generator either in the hospital where the ^{99m}Tc will be used or in a radiopharmacy. ^{99}Mo–^{99m}Tc generators are devices that help perform simple and reliable separation of ^{99m}Tc from ^{99}Mo of very high specific activity (e.g. fission product ^{99}Mo, ~10^4 curies per gram (Ci/g)) adsorbed on an acidic alumina column. The ^{99m}Tc is obtained by passing physiological saline (0.9% NaCl solution) through the alumina column. Compact generators are available that deliver high quality ^{99m}Tc.

Over 95% of the ^{99}Mo required for ^{99m}Tc generators is produced by the fission of uranium-235 (^{235}U) targets (^{99}Mo fission yield 6.1%) in nuclear research reactors (steps 1 and 2 in Fig. VII–1). The irradiated targets are then processed (step 3) and the resulting purified ^{99}Mo solution subsequently distributed for use in the production of ^{99}Mo–^{99m}Tc generators.

[45] This annex to the *Nuclear Technology Review 2010* was prepared based mostly on the situation at the beginning of February 2010. Since the situation is continuously changing, some updates as of May 2010 have been added. The additions are, however, not comprehensive.

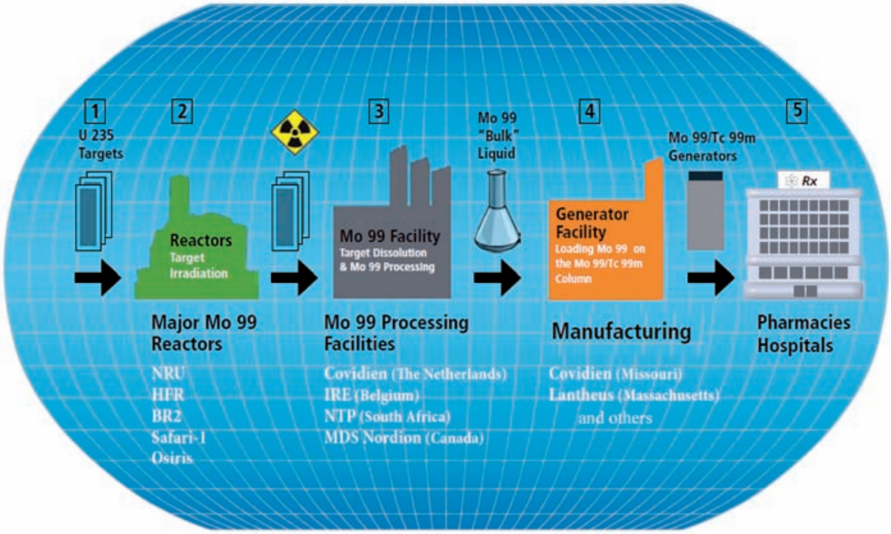

FIG. VII–1. Global supply chain of ^{99}Mo and subsequent utilization schematics. (Source: www.covidien.com, October 2009.)

Since the last quarter of 2007, the supply chain shown in Fig. VII–1 has suffered from serious repeated disruptions in the production of ^{99}Mo. This annex summarizes the current status of global ^{99}Mo supplies as well as the reasons for recent disruptions. It summarizes the possibilities being considered to address these disruptions and the status of current deliberations. The IAEA is one of several organizations that can help coordinate deliberations to raise the likelihood, speed and efficiency of joint action to increase reliable supplies of ^{99}Mo. This annex also summarizes some of the recent IAEA activities to that end.

VII–2. Production of ^{99}Mo

Five research reactors produce most of the world's ^{99}Mo (see Table VII–1). These reactors use high enriched uranium (HEU) targets, and all are over 40 years old (see Fig. VII–2). As of 2009, NRU in Chalk River, Canada, was 52 years old; BR-2 in Mol, Belgium, was 48 years; HFR in Petten, Netherlands, was 48 years; Osiris in Saclay, France, was 43 years; and Safari-1 in Pelindaba, South Africa, was 44 years. Moreover, none of these reactors is entirely dedicated to the production of ^{99}Mo and other radioisotopes. They all provide multiple services to multiple users.

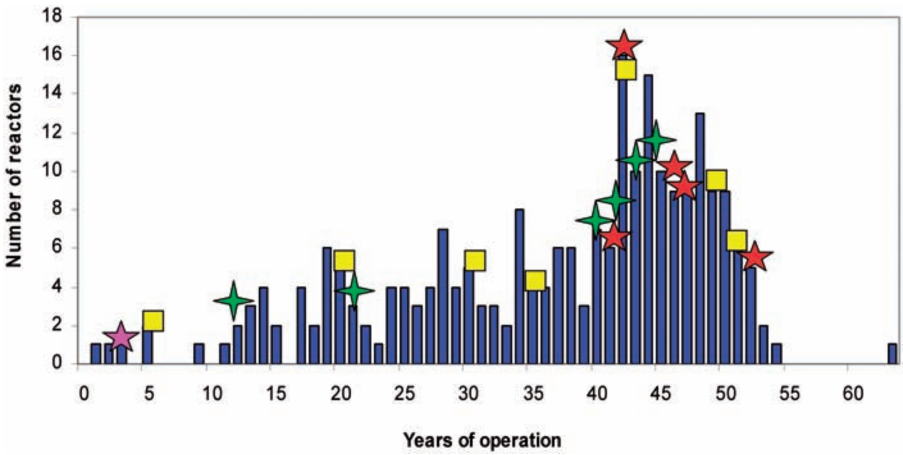

FIG. VII–2: Age distribution of the world's 245 operational research reactors. (Source: IAEA Research Reactor Database.) ★ The five major research reactors currently producing ^{99}Mo; ★ the OPAL research reactor (Australia); ✦ existing research reactors that are already used by regional ^{99}Mo producers or for which commissioning is under way; ■ existing research reactors, which are now studying the feasibility of providing irradiation services. See Tables VII–1 and VII–2 for more information.

In addition to the five major producers, the National Atomic Energy Commission (CNEA) of Argentina has been producing ^{99}Mo since 2002 using low enriched uranium (LEU) targets. CNEA's production record is an important demonstration of the use of LEU targets, even though its production represents only 1.5% of the global market. Indonesia also produces small quantities of ^{99}Mo for domestic use and some for export, for example to Bangladesh.

There are currently only four large scale facilities for processing the irradiated targets after they are removed from the reactors. Two processing methods are used, one involving acidic dissolution of the targets and the other involving alkaline digestion of the targets. Both require a series of radiochemical separation and purification steps that are very complex and require sophisticated technical skills and well equipped hot cells. Purity requirements for ^{99}Mo are very high, and extensive quality controls are essential. The demanding requirements for robust operational systems, a reliable, well trained workforce, and excellent quality management systems, together with the expense of the required technology, have best been met by commercial corporations. The four ^{99}Mo processing facilities are, as shown in Fig. VII–1, operated by MDS Nordion in Canada, the Institute for Radioelements (IRE) in Belgium, Covidien in the Netherlands, and Nuclear Technology Products (NTP) in South Africa. Their typical production shares prior to the recent production disruptions were 40%, 20%, 25% and 10%, respectively. A new facility, associated with Australia's

OPAL reactor, is expected to become available in 2010. It completed trial production runs in 2009 and obtained regulatory approvals for regular production. It will be the first large scale ^{99}Mo producer to use LEU targets and will have a production capacity of over 1000 Ci per week[46]. This is a bit more than 8% of the global market's weekly ^{99}Mo requirement of approximately 12 000 Ci.

The next major step in the chain is the production of ^{99}Mo–^{99m}Tc generators (step 4 in Fig. VII–1). This has become a well established business in a number of countries, and there are many more enterprises at this step in the chain than at the previous steps. In addition to major corporate producers, such as Lantheus Medical Imaging, GE Healthcare, Daiichi, and Covidien; the Nuclear Energy Research Institute (IPEN) in São Paolo, Brazil, the Institute of Atomic Energy in Poland, and the Atomic Energy Organization of Iran in Teheran currently produce batches of a few hundreds of generators per week. Private initiatives in generator production have also emerged in Argentina, Chile and Turkey. All these centres depend on weekly imports of fission product ^{99}Mo.

An alternative to the fission based production of ^{99}Mo shown in Fig. VII–1 is ^{99}Mo production through neutron activation of molybdenum trioxide targets in research reactors. This produces ^{99}Mo of relatively low specific activity, of the order of 0.2 to 1 Ci/g (7.4 to 37 GBq/g), depending upon the neutron flux. This product is popularly known as (n, gamma) ^{99}Mo and has been in limited use (1–2%) for producing ^{99m}Tc either through a process known as zirconium molybdate — ^{99}Mo gel generator (e.g. in China, India and Kazakhstan) or through a process using solvent extraction (e.g. in India). A facility in Chengdu, China, was the first large scale producer of gel generators and has provided up to 25% of national ^{99m}Tc requirements. Since 2006 India has produced more than 100 batches of gel generators using up to 28 Ci (1040 GBq) ^{99}Mo per batch and meeting nearly 15% of India's overall ^{99m}Tc needs. The maximum number of generators per batch is 24 and the maximum radioactivity capacity is about 1.2 Ci (44 GBq). Kazakhstan has been using the gel procedure for centralized production of ^{99m}Tc in Almaty, while development of portable generators is in progress.

[46] These are '6-day curies', meaning they are the number of curies six days after the end of the production process, which is generally eight days after irradiation in the reactor is completed.

TABLE VII–1. FISSION BASED ^{99}Mo PRODUCTION AT RESEARCH REACTORS WORLDWIDE

Existing research reactors used by large scale producers						
Country	Name	Thermal power, MW	Thermal neutron flux, n/s/cm^2	Target type	Maximum annual operation, days[a]	Typical share of production %
Canada	NRU	135	4.0e14	HEU	315	40
Netherlands	HFR	45	2.7e14	HEU	290	30
Belgium	BR-2	100	1.0e15	HEU	115	10–15
South Africa	Safari-1	20	2.4e14	HEU	315	10–15
France	OSIRIS	70	1.7e14	HEU	220	5–8
Australia	OPAL	20	3.0e14	LEU	340	yet to enter market
Poland	MARIA	30	3.5e14	HEU (for Covidien)	200	not known
Existing research reactors used by regional producers						
Country	Name	Thermal power, MW	Thermal neutron flux, n/s/cm^2	Target type	Maximum annual operation, days[b]	Potential production capacity (weekly) 6-day Ci
Argentina	RA-3	5	4.8e13	LEU	230	200 Ci
Indonesia	GA SIWABESSY MPR	30	2.5e14	HEU/LEU conversion Under way	147	150 Ci
Russian Fed.	WWR-TS	15	1.8e14	HEU	190	Not known
Russian Fed.	IRT-T	6	1.4e14	HEU	190	Not known

TABLE VII–1. FISSION BASED ^{99}Mo PRODUCTION AT RESEARCH REACTORS WORLDWIDE (cont.)

Existing research reactors to be used by regional producers (commissioning is under way)						
Country	Name	Thermal power, MW	Thermal neutron flux, n/s/cm^2	Target type	Maximum annual operation, days[b]	Potential production capacity (weekly) 6-day Ci
Egypt	ETRR-2	22	2.8e14	LEU	294	250 Ci
Pakistan	PARR-1	10	1.7e14	Not known	Data not available	Not known

[a] Source: IAEA Research Reactor Database (http://www.iaea.org/worldatom/rrdb/); National Research Council of the National Academies, 2009.

[b] Source: IAEA Research Reactor Database (http://www.iaea.org/worldatom/rrdb/).

VII–3. Disruptions in ^{99}Mo supplies and follow-up initiatives

Starting in the last quarter of 2007, several independent reactor shutdowns and outage extensions significantly disrupted global ^{99}Mo supplies. These included the extension of a planned outage at NRU in 2007 related to regulatory commitments, the extension of a planned outage at HFR-Petten in 2008 due to leaks, the prolonged shutdown of NRU from May 2009 through at least late July 2010 to repair leaks, and an unplanned shutdown of the IRE processing facility in 2008 due to an iodine-131 release from the waste stream. These unplanned events, combined with other planned outages created a worldwide ^{99}Mo supply crisis.[47] BR-2 and Safari-1 generally functioned well during the crisis without any unplanned outages, and good cooperation among producers and reactor managers helped to reduce the crisis's impact. Operating producers increased production to the extent possible, for example, at Safari-1 when NRU and HFR were shut down and at Covidien when IRE was shutdown. Nonetheless, in 2008, disruptions, i.e. cancellations or delays in patient services, ranged from 20% to 70% of planned services, depending on the week and location.

[47] HFR-Petten has been shut down since the third week of February 2010 and is expected to remain shut until the third quarter of 2010.

TABLE VII–2. EXISTING RESEARCH REACTORS WITH FEASIBILITY STUDIES UNDER WAY TO PROVIDE IRRADIATION SERVICES TO PRODUCE FISSION BASED ^{99}MO

Country	Name	Thermal power, MW	Thermal neutron flux, n/s/cm^2	Target type	Maximum annual operation, days	Potential production capacity (weekly) 6-day Ci
Germany	FRM-II	20	8.0e14	HEU (for IRE)	245	3000–4000 Ci
Canada	MNR McMaster Univ.	3	1.0e14	HEU	250	~1500 Ci
USA	MURR Univ. of Missouri	10	6.0e14	LEU	312	~3000 Ci
Chile	RECH-1	5	7.0e13	LEU	50	250 Ci
Czech Republic	LVR-15 REZ	10	1.5e14	HEU (for IRE)	210	not known
Poland	MARIA	30	3.5e14	LEU	200	not known
Romania	TRIGA II Pitesti	14	3.3e14	LEU	280	~3000 Ci

The ^{99}Mo supply chain will continue to remain fragile as long as it continues to rely on the same five aged production reactors. Some short term adjustments are possible. BR-2 will add one additional three-week cycle in 2010 to its normal schedule of reactor cycles, an addition made possible through resources contributed by manufacturers of ^{99}Mo–^{99m}Tc generators. The operating organizations of OPAL, HFR and Safari-1 have formed a cooperative group to improve operational reliability. The group is focused on non-commercial aspects of reactor operation. Operating experiences are openly shared and related challenges are discussed in depth. The formal agreements include cost recovery arrangements for resource sharing for technical support and peer review. Each facility has already taken advantage of assistance available from the others and offered assistance when asked. The initiative has also been positively received by the relevant regulatory bodies, which themselves have increased their interaction since the formation of this group.

Another short term response to the crisis was a series of meetings to discuss the difficulties of a long term solution and to map ways forward. These included expanding the scope of a 2008 Research Coordination Meeting of the IAEA CRP on ‘Developing techniques for small scale indigenous ^{99}Mo production using LEU fission or neutron activation’, discussions in Brussels in 2008 between the European Association of Nuclear Medicine (EANM) and relevant EU authorities on prospective EU actions, an IAEA side event in 2008 at EANM’s annual meeting, a meeting of the International Nuclear Regulators Association (INRA) in 2008, a 2009 meeting hosted by the French Nuclear Safety Authority (ASN) for its counterparts from Australia, Belgium, Canada, Netherlands, South Africa, UK and USA, and a 2009 workshop on ‘Security of supply of medical radioisotopes’ held in Paris at the request of Canada by the OECD/NEA. Of particular concern to regulators was their dilemma in balancing health concerns and nuclear safety concerns in the event of unplanned outages. One consequence of the Paris workshop was the establishment, by OECD/NEA, of the High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR). The IAEA is an observer in this group. The group held its first meeting in June 2009, at which it developed an action plan that included: addressing enhanced coordination among stakeholders and transparency in schedules, launching an economic analysis, and identifying possible options for additional capacity including through addressing transport related issues. One further short term response was a survey and report, by the Association of Imaging Producers and Equipment Suppliers in November 2008, on molybdenum-99 production for nuclear medicine 2010–2020[48].

The longer term challenges, as discussed in these meetings, are several. Osiris is expected to shut down in 2015, and NRU will need a licence renewal in 2011. The Canadian Government has emphasized its support for the licence renewal but has also indicated that there may be no more reactor support beyond 2016. The report of the four-member panel of the Canadian Government released in December 2009 recommends, as the preferred option, a new research reactor devoted partially to radioisotope production. It also notes that the direct production of ^{99m}Tc using available medical cyclotrons, although possibly not economically attractive, can be an option for the immediate future.[49]

[48] Available at http://www.vrom.nl/Docs/milieu/200902_AIPESMolySupplyReport.pdf.

[49] In June 2009, the Canadian Government formed a four member expert panel to review and recommend measures for meeting medical isotope production demands. The panel’s report, released in December 2009, is available at http://nrcan.gc.ca/eneene/sources/uranuc/pdf/panrep-rapexp-eng.pdf.

The European Commission has also responded to calls from its members to address the reliability of ^{99}Mo supplies in Europe. Following a number of meetings and studies to assess the situation, the Council of the European Union adopted conclusions in December 2009 calling for actions on ten points, including the coordination of efforts with other forums such as the HLG-MR and the IAEA.

As noted earlier, none of the five major reactors that produce ^{99}Mo is entirely dedicated to the production of ^{99}Mo. They were financed and built to provide multiple services to multiple users and not according to any business model designed to best serve the ^{99}Mo market. Indeed the business case for building new reactors for ^{99}Mo production is problematic. Margins are low, capital costs are high, lead times are long, and shipment denials and delays add market uncertainty, while the established existing competition, because of its history and other non-^{99}Mo activities, has government support, additional funds and no high capital costs to worry about. As will be discussed later, however, the cost of ^{99}Mo is only a small fraction of the cost of the final radiopharmaceutical dose administered to the patient. Thus, raising the price of ^{99}Mo, which might strengthen the business case in building more buffer capacity in ^{99}Mo production through additional investment, should be possible without significantly adding to the cost of the final radiopharmaceutical.

In addition to the currently weak business case for new capacity, recent experience in efforts to add new capacity has not been encouraging. In May 2008, AECL cancelled the Canadian MAPLE project, which included two reactors dedicated to ^{99}Mo production — each capable of meeting most, if not all, of global ^{99}Mo demand. The cancellation was due to commissioning challenges related to the design of the reactor core. In Australia, commissioning of the new OPAL reactor was interrupted by a ten month shutdown following the discovery of dislocated fuel plates during operation.

Nonetheless, there are a few prospective new sources of production in the pipeline. As noted earlier, ^{99}Mo production in the Australian OPAL research reactor is scheduled to become available during 2010. Production from the MARIA reactor in Poland based on the irradiation of HEU targets (for Covidien, Petten, NL) was begun in March 2010. In May, similar irradiation of HEU targets began at the Řež reactor in the Czech Republic for production at IRE's facility in Fleurus, Belgium. The FRM-II reactor in Germany is also progressing on a project to produce ^{99}Mo via HEU target irradiation by 2013 (for IRE, Fleurus, Belgium). Two additional new multi-purpose research reactors are also expected to come on line soon: JHR at Cadarache, France, in 2015 or shortly thereafter and PALLAS in the Netherlands in 2016 or later, depending on the project schedule, which has yet to be finalized. These are expected to ensure sustainable ^{99}Mo production capacity when some of the currently used reactors may be shutdown.

In the USA, there are two new LEU based production initiatives, one from the University of Missouri Research Reactor (MURR) and the other from the Babcock and Wilcox Company and Covidien. Prompted by the ^{99}Mo crisis and the USA's total dependence on ^{99}Mo imports, the US Congress passed the American Medical Isotopes Production Act of 2009, which envisages spending nearly $163 million over the next five years to establish a non-HEU domestic ^{99}Mo production process. Funding will come from the Global Threat Reduction Initiative (GTRI).

There is also scope for making greater use of the existing smaller scale production capacity noted earlier. For example, CNEA in Argentina plans to double its current production capacity. The National Nuclear Energy Agency (BATAN) in Indonesia has similar potential. Other potential new producers who are either setting up facilities (e.g. the Egyptian Atomic Energy Authority) or have appropriate facilities and capabilities (e.g. Institute of Atomic Energy in Poland) could be encouraged.

In addition to possible production from its existing appropriate facilities, the Polish Institute of Atomic Energy announced, at a September 2009 workshop in Warsaw organized by the Institute and the IAEA, plans to establish, subject to the outcome of an ongoing feasibility study, a new production facility using LEU targets. The proposed start of operations would be by 2013. Also discussed at the same meeting was the high potential for production capacity in the reactor in Piteşti, Romania.

The ^{99}Mo crisis has increased interest in alternate technologies for the production of ^{99}Mo and their corresponding development issues, specifically:

— Photofission of ^{238}U in high power electron accelerators[50];
— Aqueous homogeneous reactors[51];
— Expanding local and regional use of gel generator technology;
— Use of enriched ^{98}Mo targets and neutron activation (thermal and epithermal neutrons) along with the recovery and recycling of the enriched target; and
— Use of enriched ^{100}Mo targets by (gamma, n) in high power electron accelerators, (n, 2n) in intense fast neutron sources (e.g. the International Fusion Materials Irradiation Facility) or charged particle induced (p, 2n) reactions in medical cyclotrons.

[50] TRIUMF Mo-99 project (http://www.triumf.ca/home/news-publications/medical-isotopes).

[51] http://www.iaea.org/OurWork/ST/NE/NEFW/rrg_Mo99.html.

There is also interest in developing additional methods for utilizing (n, gamma) ^{99}Mo, as reflected in work on a high affinity adsorbent for molybdenum in Japan (polyzirconium compound) as well as Australia and India (poly titanium oxochloride), and on an electrochemical separation approach in India. It is possible to obtain (n, gamma) ^{99}Mo of relatively higher specific activity if a higher epithermal neutron flux profile is available in the reactor, since in this case the activation cross-section is nearly 50 times higher. This strategy is being explored at Dimitrovgrad, Russian Federation, which has a reactor with the appropriate features.

There is also the possibility of directly producing ^{99m}Tc by the reaction ^{100}Mo(p, 2n), which would take advantage of the very large number of medical cyclotrons (mainly proton accelerators in the 16–19 MeV range) in regular operation around the world and dedicated for medical isotope production. However, yields would be better at proton energies of 20–25 MeV, and, because the natural abundance of ^{100}Mo is only 9.63%, very highly enriched ^{100}Mo targets are necessary for ensuring adequate radionuclide purity of ^{99m}Tc to be suitable for medical use. The technology for recovering and recycling enriched ^{100}Mo targets would need to be further developed, and the economics of daily direct production of ^{99m}Tc in the required quantities is not likely to be competitive compared to ^{99}Mo–^{99m}Tc compact generators.

The question of alternatives to ^{99m}Tc has also been considered, for example, use of thallium-201 for myocardial single photon emission computed tomography (SPECT) imaging and fluorine-18 (as sodium fluoride) for bone PET scanning. While these could serve to a limited extent in certain centres, large scale adoption of these products, or other equivalent PET tracers, matching the volume of procedures possible with ^{99m}Tc products will not be practicable, even in developed countries.

Techniques other than those of nuclear medicine are also being considered in terms of comparative advantage. Cardiac studies might be slightly affected by the introduction of computed tomography (CT) angiography, more likely in developed countries. However, in many cases coronary CT angiography might itself raise an additional need for a SPECT scan for a better functional evaluation of possible anomalies detected on the coronary vessels. For the other important application of nuclear medicine in oncology (bone scanning to detect bony metastatic involvement), which is widely used in developing countries, there are no foreseeable alternatives.

VII–4. ^{235}Uranium targets: HEU and LEU

Strategies to increase the reliability of ^{99}Mo supplies must also take into account international efforts to shift from HEU to LEU to strengthen nuclear security. Currently, over 95% of ^{99}Mo production uses HEU targets. About 40–50 kg of HEU per year is used, with less than 5% of the original ^{235}U in the targets consumed during irradiation. Thus a large amount of HEU is left behind in the waste. A 2007 meeting in Sydney under the auspices of the Global Initiative to Combat Nuclear Terrorism detailed the technical and economic aspects and requirements for converting to LEU targets and concluded the following.

- There are no scientific barriers to the production of ^{99}Mo using LEU; small to medium scale production has already been demonstrated.
- The challenge is to move beyond the demonstration of the technical feasibility of the LEU target process to the commercial demonstration of a regular large scale production capability.
- Converting HEU ^{99}Mo facilities to LEU ^{99}Mo requires long lead times and resources. Conversion could take eight years or more.
- Adoption of the LEU process by new entrants to the business ('greenfields') and the conversion of existing facilities using the HEU process ('brownfields') will involve different pathways and needs.

In 2009, the National Research Council of the National Academies in the USA published a report on the feasibility of procuring supplies of medical isotopes from commercial sources that do not use HEU.[52] The report contains a detailed comprehensive account of all the issues and is expected to have a significant effect on strategies for producing ^{99}Mo in the future. It includes specific recommendations to the US Congress, such as cost sharing for conversion related R&D, a 7–10 year phase-out of HEU exports, and continuing government assistance to improve ^{99}Mo supply reliability.

In 2009, national authorities in the USA and Canada approved the use of ^{99}Mo produced by LEU fission, for example by the OPAL reactor, as an active pharmaceutical ingredient. This is an important milestone in the adoption of LEU based ^{99}Mo for regular use not only in these two countries but also for other generator production centres around the world.

In June 2009, the conversion of Safari-1's core to LEU fuel was completed. Nuclear Technology Products (NTP), working with Safari-1, reported considerable progress on converting targets to LEU. This is the first concrete step towards LEU target conversion by a major ^{99}Mo producer. A number of challenges still need to be addressed, but conversion should be simpler in this case since Safari-1 uses ^{235}U targets that are enriched only up to 46%, compared

[52] The executive summary is available at http://www.nationalacademies.org/.

to 93% targets used by other producers. The conversion to LEU targets is expected to reduce Safari-1's ^{99}Mo production capacity by about 20%.

VII–5. IAEA activities and findings from recent meetings

The IAEA has been involved for more than three decades in fostering developments in ^{99}Mo-^{99m}Tc generator systems. It has coordinated a number of CRPs, with one currently under way on the production of ^{99}Mo using LEU targets or neutron activation. It arranges expert reviews through technical and consultants meetings, and it publishes technical documents. Examples are:

- *Fission molybdenum for medical use,* IAEA-TECDOC-515 (1989);
- *Alternative technologies for $^{99}Tc^{m}$ generators,* IAEA-TECDOC-852 (1995);
- *Management of radioactive waste from ^{99}Mo production,* IAEA-TECDOC-1051 (1998);
- *Production technologies for molybdenum-99 and technetium-99m* IAEA-TECDOC-1065 (1999);
- *Homogeneous aqueous solution nuclear reactors for the production of Mo-99 and other short lived radioisotopes* IAEA-TECDOC-1601, (2008);
- *Research reactor modernization and refurbishment* IAEA-TECDOC-1625 (2010);
- *Optimization of research reactor availability and reliability: recommended practices,* IAEA Nuclear Energy Series No. NP-T-5.4 (2008).

The IAEA has also supported interested Member States in establishing and/or operating ^{99m}Tc generator production facilities, for example in Bangladesh, China, Indonesia, Islamic Republic of Iran, Pakistan and the Syrian Arab Republic. The IAEA supports the effective operation and utilization of research reactors, which include tasks related to irradiation services and isotope production. The IAEA also fosters coalitions of research reactor operators and users to improve utilization of their facilities, and a topic of interest for coalition members is isotope production as a possible business opportunity. IAEA support for strengthening operational performance of research reactors is also aimed at enhancing the reliability of radioisotope supplies in general and ^{99}Mo in particular.

The IAEA has a number of activities under way to foster the use of LEU targets as well as to help identify and expand the number of reactors engaged in the production of ^{99}Mo. These include the CRP cited earlier on 'Developing Techniques for Small Scale Indigenous ^{99}Mo Production using LEU Fission or

Neutron Activation'[53], encouraging potential facilities to become actual producers (e.g. Egypt), and the establishment of research reactor coalitions to expand and strengthen networks of reactors capable of providing irradiation services (e.g. Poland and Romania). The CRP involves several countries with the potential to become small to medium scale ^{99}Mo producers using LEU targets. Some have made important progress, for example Egypt and Pakistan, on setting up processing facilities. Others have advanced plans, for example Poland and Romania. Egypt and Pakistan are also setting up full-fledged facilities to produce ^{99}Mo based on LEU fission with assistance from INVAP of Argentina and from Isotope Technologies — Dresden of Germany, respectively. Hot commissioning runs are taking place through the first quarter of 2010 in Egypt, and the envisaged capacity is 250 6-day Ci per week.

The IAEA is also reviewing additional production options together with key stakeholders and encouraging potential partnership proposals. One approach under consideration is to provide irradiation services in existing research reactors with suitable features, facilities and operational cycles, and then transport the irradiated HEU targets to existing processing facilities. Obtaining approvals from national authorities for transporting the irradiated targets will be crucial for the success of this approach. Moreover, reactor operators will need to be assured that there will be a continuing reliable demand to justify making the investments to provide such irradiation services. Three specific arrangements to meet immediate and medium term needs are being pursued as follows:

— Covidien, Petten-NL with the MARIA reactor of the Institute of Atomic Energy, Poland (begun in March 2010);
— IRE, Fleurus, Belgium with the FRM-II reactor of the Technical University Munich (TUM), Germany (target: by 2013);
— IRE, Fleurus, Belgium with LVR-15 reactor of the Nuclear Research Institute Řež, Czech Republic (begun in May 2010).

With IAEA support, the Eurasia Research Reactor Coalition has been established incorporating four reactors in Central Asia and Eastern Europe and one processing facility in Hungary (see Fig. VII–3). It is considering collaborative plans for producing ^{99}Mo using neutron activation of enriched ^{98}Mo targets and, by the third quarter of 2010, aims to increase ^{99}Mo supplies for ^{99m}Tc generators with capacities up to about 0.4 Ci (15 GBq); higher capacity

[53] More details are available at http://www.iaea.org/OurWork/ST/NE/NEFW/rrg_Mo99.html.

FIG. VII–3. Geographical distribution of Eurasia Research Reactor Coalition: Four research reactors in Czech Republic, Kazakhstan, Ukraine and Uzbekistan (stars), an isotope processing facility in Hungary (square) and a number of partners in the USA (spheres).

generators will also be feasible after blending with fission-produced molybdenum.[54]

Much of the emphasis in recent studies and meetings triggered by the disruption in ^{99}Mo supplies is on the economics of the front end of the fission-based ^{99}Mo-^{99m}Tc supply chain. The reactor services are not adequately compensated for their support to ^{99}Mo production. High costs for new reactors and for new ^{99}Mo processing facilities, low margins and the added risk of occasional transport delays and denials all discourage investment. Even for an existing reactor with potential additional capacity, the business case for using that potential is unclear.

One possibility is to look to the ^{99m}Tc generator production industry as a potential source of investment in ^{99}Mo production facilities given their existing role in the ^{99}Mo–^{99m}Tc supply chain and special interest in reliable ^{99}Mo supplies. A second possibility arises from the fact that the cost of ^{99}Mo is only a fraction of the ^{99m}Tc generator cost, and even less when compared to the cost of the final radiopharmaceutical dose to be administered to the patient. This implies that a needs-based increase in the price of ^{99}Mo should not have a major impact on the

[54] More information can be found at http://www.iaea.org/OurWork/ST/NE/NEFW/rrg_EARRC.html.

cost of patient services. The US National Research Council of the National Academies report cited earlier includes some analysis of this issue and comments on the economics of ^{99m}Tc dose as follows (recognizing that the study is from a US perspective):

> "A 10 percent increase in the cost of the ^{99}Mo that is used to produce the ^{99m}Tc doses would translate to about a 0.1 percent increase in the prices of patient procedures. A 10 percent increase in the price of a ^{99m}Tc dose itself would only translate to about a 0.4 percent increase in patient procedure prices."

In other words, even if the ^{99}Mo price were to be considerably increased, the net effect on the final cost of the ^{99m}Tc dose should only be marginal. The reality of commercial requirements and practices at different stages of the production chain may, however, lead to a much higher increase than indicated in the US report.

One additional study to be completed during the first quarter of 2010 is an economic analysis of the ^{99}Mo-^{99m}Tc supply chain by the new OECD/NEA High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR) that was mentioned earlier. Among other things, HLG-MR is expected to assess the future demands for ^{99}Mo, and address the disincentives created by transport related issues, namely shipment delays and denials and lack of mutual recognition of container licenses. The IAEA's assistance is sought to facilitate harmonized licensing procedures, mutual recognition of container licenses, and ground transport of irradiated uranium targets from reactor sites to existing processing facilities.

VII–6. Concluding remarks

The ^{99}Mo supply chain will continue to remain fragile as long as it continues to rely on the same five aged production reactors. Given the way the supply chain has evolved — particularly its reliance on only five multipurpose, non-commercial, government supported research reactors — there are no clear market incentives to prompt new capacity or alternative supplies. Yet all agree that reliable supplies of ^{99}Mo for medical procedures are essential. ^{99}Mo supply challenges since 2008 have led to the initiation and/or acceleration of multiple ^{99}Mo production projects. Completion of some of these, for meeting supply needs in the near future, will require HEU targets to be irradiated in more reactors and transported along new routes and over greater distances than is currently the case. Coordinated interventions and support by governments are therefore necessary to both ensure the reliability and long term sustainability of ^{99}Mo supply as well as to achieve international, non-proliferation goals related to the minimization of HEU use in civilian applications.

Although any direct IAEA contributions to increased production will necessarily be very limited, the IAEA will continue to help coordinate deliberations and promote joint action to the full extent of its capabilities, in close coordination with OECD/NEA and EC initiatives.

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10-13671

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