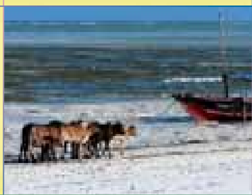
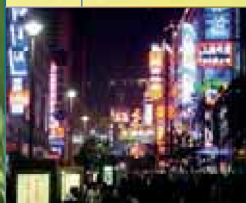
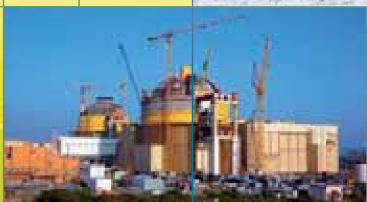
NUCLEAR TECHNOLOGY REVIEW

2009



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NUCLEAR TECHNOLOGY REVIEW 2009

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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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EXECUTIVE SUMMARY

The year 2008 was paradoxical for nuclear power. Projections of future growth were revised upwards, but no new reactors were connected to the grid. It was the first year since 1955 without at least one new reactor coming on-line. There were, however, ten construction starts, the most since 1985.

At least until the global financial crisis, cost estimates reported for new nuclear reactors were often higher than those in previous years, particularly in regions with less recent experience in new construction. However, growth targets for nuclear power were raised in the Russian Federation, and similar considerations were under review in China. India negotiated a safeguards agreement with the Agency in August, and the Nuclear Suppliers Group subsequently exempted India from previous restrictions on nuclear trade, which should allow India to accelerate its planned expansion of nuclear power.

In the USA, the Nuclear Regulatory Commission (NRC) received combined licence (COL) applications for 26 new reactors. The US Department of Energy (USDOE) received 19 ‘Part I applications’ for Federal loan guarantees to build 21 new reactors.

Nonetheless, current expansion, as well as near term and long term growth prospects, remain centred in Asia. Of the ten construction starts in 2008, eight were in Asia. Twenty-eight of the 44 reactors under construction at the end of the year were in Asia, as were 28 of the last 39 new reactors to have been connected to the grid.

Armenia joined the Russian Federation and Kazakhstan as members of the International Uranium Enrichment Centre in Angarsk, Siberia. The Ukrainian Government announced that Ukraine would also join. AREVA and USEC applied to the USDOE for loan guarantees for the construction of AREVA’s proposed Eagle Rock Enrichment Facility and USEC’s American Centrifuge Plant.

Construction of an underground repository for low and medium level radioactive waste began at the former Konrad iron mine in Germany. The USDOE submitted a formal application to build and operate the long planned high level waste repository at Yucca Mountain in Nevada.

The ITER International Fusion Energy Organization formally applied for a construction permit to build the International Thermonuclear Experimental Reactor (ITER), an experimental fusion reactor, in Cadarache, France.

Water resource management, food security, human health, environmental protection and the use of radioisotopes and radiation are all areas where nuclear and isotopic techniques are making valuable contributions to socioeconomic development around the world.

In the food and agriculture area, nuclear techniques are being used, together with complementary techniques, to enhance livestock productivity as well as to prevent the spread of dangerous transboundary animal diseases such as avian flu. As international trade expands, the need to ensure food safety also grows. Isotopic techniques are being used to trace the origin of foods and to track the infiltration of contaminants as a means to ensure the quality of food products.

Nuclear imaging is playing a growing role in the development of new drugs. Interventions to improve nutrition are increasingly becoming part of development strategies; the use of stable isotopes to assess key nutritional aspects, such as body composition, can be part of effective strategies to counteract later development of chronic diseases. The long sought 'magic bullet', where a truly targeted substance kills cancer cells without damaging healthy tissue, is progressively, albeit slowly, becoming a reality in therapeutic nuclear medicine.

In the natural resources management field, nuclear techniques are helping to assess 'hot particles' — a type of radionuclide that can be released to the environment from a number of sources including weapons testing and nuclear accidents. Stable isotopes are being used in order to gain a better understanding of complex food webs and carbon cycling in the marine environment. Radiotracer tools are being utilized to measure the impacts of climate change, such as ocean acidification on marine biodiversity. Isotope methods are increasingly being used to assist in the easy identification of aquifers with old water and no recharge, or with modern water with significant recharge, which is important information for effective freshwater management.

Global demand for radioisotope and radiation sources is growing due to their use in medicine and industry with a corresponding expansion of regional centres for the production of clinical radiotracers for positron emission tomography imaging. During the past year, disruptions in the supplies of the radioisotope molybdenum-99, the source of widely used technetium-99m for diagnostic imaging, had a negative impact on patient services in nuclear medicine centres around the world. Governmental support and stronger cooperation among isotope manufacturers including public–private partnerships will be required to ensure that suitable reactors will be engaged in the irradiation of low enriched uranium targets for molybdenum-99 production in the future.

A. POWER APPLICATIONS

A.1. Nuclear power today

Worldwide, there were 438 nuclear power reactors in operation at the end of 2008. No new reactors were connected to the grid in 2008, and Bohunice-2 was retired at the end of the year in line with Slovakia's European Union (EU) accession agreement. Worldwide nuclear generating capacity as well as nuclear power's share of global electricity generation remained essentially unchanged at 372 GW(e) and at 14%, respectively (see Table A-1).

There were ten construction starts in 2008: Fangjiashan-1, Fuqing-1, Hongyanhe-2, Ningde-1 and -2 and Yangjiang-1 (all 1000 MW(e)) in China, Novovoronezh 2-1 and Leningrad 2-1 (both 1085 MW(e)) in the Russian Federation, and Shin-Wolsong-2 (960 MW(e)) and Shin-Kori-3 (1340 MW(e)) in the Republic of Korea. This compares with eight construction starts plus the resumption of active construction at one reactor in 2007. In 2006, there were four construction starts plus resumed construction at one reactor.

Current expansion, as well as near term and long term growth prospects, remain centred in Asia. Of the ten construction starts in 2008, eight were in Asia. As shown in Table A-1, 28 of the 44 reactors under construction at the end of the year were in Asia, as were 28 of the last 39 new reactors to have been connected to the grid. China is considering raising its target for nuclear power's share of electricity by 2020. India negotiated a safeguards agreement with the Agency, and subsequently the Nuclear Suppliers Group exempted India from previous restrictions on nuclear trade. Less restricted trade should allow India to accelerate its planned expansion of nuclear power.

Targets were raised in the Russian Federation — to 52–59 GW(e) of nuclear power capacity by 2020. The Russian Federation also licensed the Kola-1 nuclear power plant for extended operation through July 2018, i.e. a currently licensed lifetime of 45 years.

Also in Europe, the United Kingdom published a White Paper in January 2008 that stressed that it was in the public interest for nuclear energy to continue to form part of the United Kingdom's low carbon energy mix in order to help meet carbon reduction targets and ensure secure energy supplies. Several European utilities expressed interest in building new reactors in the United Kingdom. Italy announced plans for reestablishing the legal, regulatory and technical infrastructure necessary to restart its nuclear power programme, which had been shut down following a referendum in 1987. A bill overturning the nuclear moratorium was approved by the lower chamber of the Parliament in early November. In Romania, partners signed an investment agreement to finance construction of Cernavoda-3 and 4. In Bulgaria, partners signed contracts for the construction of Belene-1 and 2. In Finland, Teollisuuden Voima Oyj (TVO) applied to the Council of State for approval in principle to build Olkiluoto-4, and two further applications are being prepared by other companies. In Switzerland, Atel, Axpo and BKW FMB Energy have submitted applications to build new nuclear power plants in Niederamt, Beznau and Gösgen. In Slovakia, Slovenské elektrárne launched a tender for the resumption of construction at Mochovce-3 and 4.

In Canada, Ontario's provincial government selected Darlington as the site for two new reactor units following Ontario Power Generation's 2006 application for a site preparation licence. Ontario Power Generation was also granted licences to operate the Darlington and Pickering-B reactors for another five years, through 2013.

In the USA, the Nuclear Regulatory Commission (NRC) approved ten power uprates, totalling 2178 MW(th). It approved three licence renewals of 20 years (for a total licensed life of 60 years) bringing the total number of approved licence renewals at the end of 2008 to 51. Concerning new construction, the NRC received combined licence (COL) applications for 26 new reactors. The US Department of Energy (USDOE) received 19 'Part I applications' for Federal loan guarantees to build 21 new reactors. The total requested was $122 billion, significantly more than the $18.5 billion offered.

Interest in starting new nuclear power programmes remains high. In the past two years, 55 Member States have expressed, through requests to the Agency to participate in technical cooperation projects, their interest in considering the introduction of nuclear power.

The Agency assists interested Member States both in analysing energy options and in preparing to introduce nuclear power and/or uranium production. The number of approved technical cooperation (TC) projects on analysing energy options increased from 29 to 41 for the technical cooperation project cycle starting in 2009. The number of projects on uranium exploration and mining increased from 4 to 10, and the number of projects on introducing nuclear power increased from 13 to 44. The Agency introduced a new service providing integrated advice to countries considering the introduction of nuclear power. In 2007 and 2008, ten such missions took place, to Belarus, Egypt, Jordan, Nigeria, Philippines, Sudan, Thailand, and to members of the Cooperation Council for the Arab States of the Gulf (three times). The Agency also provides guidance documents. In 2008, it published *Evaluation of the Status of National Nuclear Infrastructure Development* and *Financing of New Nuclear Power Plants* to supplement two basic publications in 2007, *Considerations to Launch a Nuclear Power Programme* and *Milestones in the Development of a National Infrastructure for Nuclear Power*.

TABLE A-1. Nuclear power reactors in operation and under construction in the world (as of 31 December 2008)[a]

Country	Reactors in Operation		Reactors under Construction		Nuclear electricity Supplied in 2008		Total operating Experience through 2008	
	No of units	Total MW(e)	No of units	Total MW(e)	TW·h	% of Total	Years	Months
Argentina	2	935	1	692	6.9	6.2	60	7
Armenia	1	376			2.2	39.4	34	8
Belgium	7	5 824			43.4	53.8	226	7
Brazil	2	1 766			13.2	3.1	35	3
Bulgaria	2	1 906	2	1 906	14.7	32.9	145	3
Canada	18	12 577			88.3	14.8	564	2
China	11	8 438	11	10 220	65.3	2.2	88	3
Czech Republic	6	3 634			25.0	32.5	104	10
Finland	4	2 696	1	1 600	22.1	29.7	119	4
France	59	63 260	1	1 600	419.8	76.2	1 641	2
Germany	17	20 470			140.9	28.8	734	5
Hungary	4	1 859			13.9	37.2	94	2
India	17	3 782	6	2 910	13.2	2.0	301	4
Iran, Islamic Republic of			1	915				
Japan	55	47 278	2	2 191	241.3	24.9	1 386	8
Korea, Republic of	20	17 647	5	5 180	144.3	35.6	319	8
Lithuania	1	1 185			9.1	72.9	42	6
Mexico	2	1 300			9.4	4.0	33	11
Netherlands	1	482			3.9	3.8	64	0

TABLE A-1. Nuclear power reactors in operation and under construction in the world (as of 31 December 2008)[a] (cont.)

Country	Reactors in Operation		Reactors under Construction		Nuclear electricity Supplied in 2008		Total operating Experience through 2008	
	No of units	Total MW(e)	No of units	Total MW(e)	TW·h	% of Total	Years	Months
Pakistan	2	425	1	300	1.7	1.9	45	10
Romania	2	1 300			10.3	17.5	13	11
Russian Federation	31	21 743	8	5 809	152.1	16.9	963	4
Slovakia	4	1 711			15.5	56.4	128	7
Slovenia	1	666			6.0	41.7	27	3
South Africa	2	1 800			12.8	5.3	48	3
Spain	8	7 450			56.5	18.3	261	6
Sweden	10	8 996			61.3	42.0	362	6
Switzerland	5	3 220			26.3	39.2	168	10
Ukraine	15	13 107	2	1 900	84.5	47.4	353	6
United Kingdom	19	10 097			48.2	13.5	1 438	8
United States of America	104	100 683	1	1 165	806.7	19.7	3 395	9
Totalb, c	438	371 562	44	38 988	2 597.8	14	13 475	7

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

[b] The total includes the following data in Taiwan, China:
— 6 units, 4949 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 39.3 TW·h of nuclear electricity generation, representing 17.5% of the total electricity generated there;
— 164 years, 1 month of total operating experience at the end of 2008.

[c] The total operating experience includes also shut down plants in Italy (81 years) and Kazakhstan (25 years, 10 months).

A.2. Projected growth for nuclear power

Each year the IAEA updates its low and high projections for global growth in nuclear power. In 2008, both the low and high projections were revised upwards. In the updated low projection, global nuclear power capacity reaches 473 GW(e) in 2030, compared to a capacity of 372 GW(e) at the end of 2008. In the updated high projection it reaches 748 GW(e).

The International Energy Agency (IEA) also revised its reference projection for nuclear power in 2030 upwards by about 5%.[1] However, at 433 GW(e) of installed nuclear capacity in 2030, the IEA reference scenario is still below the IAEA low projection. The IEA also published two climate policy scenarios. The '550 policy scenario', which corresponds to long term stabilization of the atmospheric greenhouse gas (GHG) concentration at 550 parts per million of CO_2, equates to an increase in global temperature of approximately 3°C. The '450 policy scenario' equates to a rise of around 2°C. In the 550 policy scenario, installed nuclear capacity in 2030 is 533 GW(e). In the 450 policy scenario it is 680 GW(e).

The OECD Nuclear Energy Agency (OECD/NEA) published a *Nuclear Energy Outlook* in 2008, which included low and high projections of nuclear power capacity through 2050.[2] For 2030, the projected range is 404–625 GW(e), somewhat below the IAEA's. For 2050, the projected range is 580–1400 GW(e).

The US Energy Information Administration also revised its reference projection for nuclear power in 2030 slightly upwards to 498 GW(e).[3] It is thus slightly higher than the IAEA's low projection.

All these projections were made before the financial crisis in late 2008. At the time of writing, no projections had been published that analysed the consequences of the crisis for nuclear power.

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[1] OECD International Energy Agency, *World Energy Outlook 2008*, OECD, Paris (2008).

[2] OECD Nuclear Energy Agency, *Nuclear Energy Outlook 2008*, OECD, Paris (2008).

[3] Energy Information Administration, *International Energy Outlook 2008*, US Department of Energy, Washington, DC (2008).

A.3. Fuel cycle[4]

The Global Nuclear Energy Partnership (GNEP), begun in 2007, grew to 25 partners in 2008. GNEP's Infrastructure Development Working Group initiated a resource library of references, programmes, tools and pooled resources to support the sharing of educational resources, the promotion of technical educational opportunities and the establishment of new training and education programmes. It also started a number of feasibility studies for GNEP members considering nuclear energy for the first time. GNEP's Reliable Nuclear Fuel Services Working Group completed a survey of the members' legal and institutional frameworks for the fuel cycle to identify common challenges. Its subsequent focus is on issues concerned with the back end of the fuel cycle.

A.3.1. Uranium resources and production

The 22nd edition of the OECD/NEA–IAEA 'Red Book'[5] reported an increase in uranium resources, reflecting recent growth in exploration activities worldwide. The increase in reported resources is a continuing trend. Over the past 14 years (seven Red Book editions), reported remaining uranium resources have increased by more than 2.4 million tonnes, despite more than 0.5 million tonnes having been mined.

The reported identified resources (5.5 million tonnes natural uranium (t U)) would last 83 years at the current rate of consumption of about 70 000 tonnes per year. This figure of 83 years can, however, be misleading because all mineral resource figures change with commodity price developments, and uranium is no exception. The reported increase in resources from 2005 to 2007 corresponds to 11 years of 2006 uranium demand, a powerful demonstration of the impact of increased uranium prices on total resource numbers. Moreover, the reported uranium resource figures presented in the Red Book are only a part of the already known resources and are not an inventory of the total amount of recoverable uranium. Examples where uranium resources are known, but not reported, are Australia, the Russian Federation and the USA.

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[4] 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/Anrep2008/) and at http://www.iaea.org/OurWork/ST/NE/NEFW/index.html.

[5] OECD/NEA and IAEA, *Uranium 2007: Resources, Production and Demand*, OECD, Paris (2008).

The projected lifetime of reported identified uranium resources of 83 years at the current consumption rate compares favourably to reserves of 30–50 years for other commodities (e.g. copper, zinc, oil and natural gas). However, demand is projected to grow, and resources in the ground need to be mined. Existing, committed, planned and prospective uranium production facilities could satisfy uranium requirements in the Agency's high projection through about 2025, provided existing mines are expanded and new ones opened as planned. Additional uranium demand would have to be met through the establishment of further mining capacity beyond what is planned. This is expected to be forthcoming as firm orders for new nuclear build are placed (in the case of the Agency's high projection) instilling confidence in uranium producers of long term rising sales prospects. Some uncertainty about the volume of fresh uranium needed to meet demand comes from the continued, albeit decreasing, availability of secondary sources. Today, secondary sources supply about 40% of demand.

In 2008, Kazakhstan started several new in situ leaching (ISL) operations and expanded several more ISL operations to their full targeted capacity in line with the country's targeted production of 10 000 t U per year in 2010. Many of the ISL operations have capacities of at least 1000 t U per year. Ground was broken in 2008 for a new uranium processing plant at Tummalapalle in Andhra Pradesh, India, with a design capacity of 220 t U per year.

A.3.2. Conversion, enrichment and fuel fabrication

Total global conversion capacity is about 75 000 tonnes of natural uranium per year for uranium hexafluoride (UF_6) and 4500 t U per year for uranium dioxide (UO_2). Current demand is about 70 000 t U per year. AREVA plans to start construction of its new COMURHEX II conversion facility in 2009, with an initial planned capacity for UF_6 conversion of 15 000 t U per year in 2012.

Total global enrichment capacity is currently about 50 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, and all are scheduled to start operation in 2009. Georges Besse II and ACP are intended to allow the retirement of existing gas diffusion enrichment plants. AREVA and USEC applied to the USDOE for loan guarantees for construction of USEC's ACP and AREVA's proposed Eagle Rock Enrichment Facility. Armenia joined the Russian Federation and Kazakhstan as members of the International Uranium Enrichment Centre

(IUEC) in Angarsk, Siberia, and, in December, the Ukrainian Government announced that Ukraine would also join.

Total global fuel fabrication capacity is currently about 11 500 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 12 000 t U per year. Some expansion of current facilities is under way, for example in China and the Republic of Korea. A new facility to fabricate mixed oxide (MOX) fuel is under construction at Rokkasho, Japan, and is scheduled for completion in 2012.

A.3.3. Back end of the fuel cycle

The total amount of spent fuel discharged globally was projected to reach 324 000 tonnes of heavy metal (t HM) by the end of 2008. Of this amount, about 95 000 t HM have already been reprocessed, 16 000 t HM are currently stored to be reprocessed and 213 000 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 6000 t HM per year. In the United Kingdom, the Thorp nuclear fuel reprocessing plant at Sellafield restarted commercial operations in 2007, three years after it was closed following a radioactive leak. Tests at the new Rokkasho reprocessing plant took longer than expected, and commercial operation was postponed until 2009.

Construction of an underground repository for low and medium level radioactive waste began at the former Konrad iron mine in Germany. It is scheduled to start accepting waste in early 2014.

Hungary's Bataapati permanent repository for low and intermediate level radioactive waste was inaugurated in 2008. Waste will be temporarily stored in a receiving area until the rock caverns for permanent disposal are opened in 2010.

The Swedish Nuclear Fuel and Waste Management Company (SKB), which is responsible for storing Swedish nuclear waste, was granted an operating licence for expanding the central interim storage facility for spent nuclear fuel at Oskarshamn from a capacity of 5000 t HM to 8000 t HM.

The USDOE submitted a formal application to the NRC for a licence to build and operate the long-planned high level waste repository at Yucca Mountain in Nevada. The repository is designed to hold 70 000 t HM of spent nuclear fuel, including 7000 t HM of military waste.

Worldwide decommissioning statistics remained unchanged in 2008: ten power reactors around the world have been completely decommissioned with their sites released for unconditional use; seventeen reactors have been partially dismantled and safely enclosed; thirty-two are being dismantled prior to eventual site release; and thirty-four reactors are undergoing minimum dismantling prior to long term enclosure.

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

A.4.1. Economics

The last time the *Nuclear Technology Review* summarized cost estimates for new nuclear power plants was in 2006. That summary compared estimates from seven studies published between 2003 and 2005. Their estimates of overnight costs ranged from \$1200/kW(e) to \$2510/kW(e).[6]

In the past year, the range of estimates has grown at its upper end. Figure A-1 shows the minimum and maximum values of recent estimates collected by the Agency from publicly available sources.

There is no definitive explanation of either the increased uncertainty in cost estimates (i.e. the wider range) or the escalation in cost estimates (i.e. the higher range) although several possible contributing factors have been suggested. Moreover, the cost estimates reflected in Figure A-1 were made before the financial crisis in late 2008. At the time of writing, the impact of the financial crisis on nuclear power cost estimates was still unclear. This section therefore summarizes factors that may have contributed to increased cost estimates and increased uncertainty, but, in the absence of rigorous studies, it cannot offer a definitive explanation.

This section focuses on overnight costs, but interest during construction (IDC) is also a major cost component for nuclear reactors. IDC estimates tend to be more tightly held by financiers, owners and shareholders and are more project-specific than overnight costs. Thus, it is difficult to assemble a meaningful graph of total costs (including IDC) comparable to Fig. A-1 for overnight costs. However, adding IDC can as much as double total project costs, particularly if factors like the construction time, interest rate or market

[6] 'Overnight costs' exclude interest, finance and escalation costs during construction — as if the plant were being built overnight. Escalation costs reflect price increases during construction. They should not be confused with contingency costs, which relate only to unforeseen work.

conditions change adversely in the midst of the project. The importance of IDC should thus not be overshadowed by this section's focus on overnight costs.

Uncertainties in cost estimates

One reason for the variation in cost estimates is that different people use different definitions. Cost components that are sometimes included, and sometimes excluded, are costs associated with bid evaluation, site selection and preparation, licensing costs, owner's and contingency costs, and some financing costs.

Some variations are due to local differences. Building on a green field site is generally more expensive than building on a site with existing reactors. Building in a more seismically active area is more expensive. Labour and material costs vary, and their impact varies with the localization rate, i.e. the percentage of plant components that are locally manufactured or procured. Subsidies and financial guarantees for nuclear power investments are different

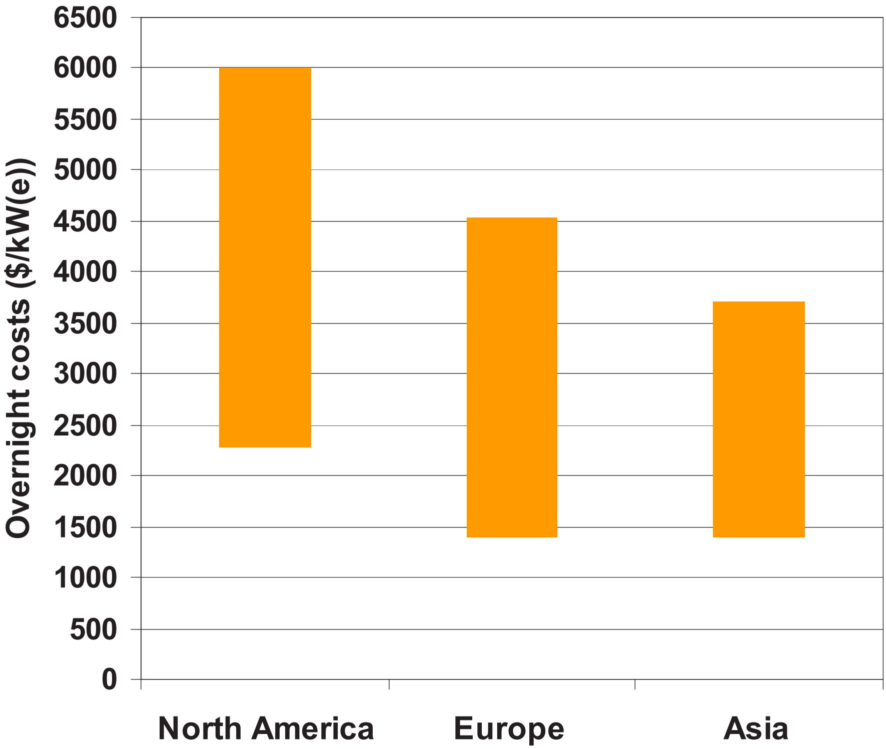

FIG. A-1. Minimum and maximum estimates of overnight costs for new nuclear power reactors, by region: 2007–2008.

in different countries and regions. Regulatory requirements can differ, as can the predictability of such requirements. Experience usually reduces uncertainty — a fact that appears to be reflected in Fig. A-1. The region with the most recent experience in building new reactors, Asia, has the lowest cost estimates and the least uncertainty. The region with the least recent experience, North America, has the highest estimates and greatest uncertainty.

Contractual arrangements also affect cost estimates. A turnkey contract might be more expensive than a cost-plus contract if the vendor prices any completion risks into the turnkey contract. Exchange rates, expectations about inflation, and their differential effects on different cost components introduce additional variability.

Different technologies have different costs. Proven designs may cost less than first-of-a-kind reactors, and building a first-of-a-kind reactor will likely cost more than building subsequent reactors of the same design. Different estimates also incorporate different learning rates in anticipating how costs will decrease with experience.

Different perspectives can also lead to different estimates. A 2006 report by the United Kingdom's Sustainable Development Commission stated that vendors of reactor systems had a clear market incentive, especially ahead of contractual commitments, to underestimate costs.[7] Utilities may have a tendency to be more conservative.

Increases in cost estimates

Possible contributors to increased cost estimates for new reactors were tighter commodity markets and steep increases through much of 2008 in international prices for steel, cement, energy, and other construction inputs. These increases also affected cost estimates for other sorts of power plants, but, because capital costs are higher for nuclear power, it is affected more.[8] In late 2008, the rise in most commodity prices reversed[9], partly for cyclical reasons (previous high prices both stimulated additional production capacity and lowered demand) and partly because of the financial crisis.

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[7] UNITED KINGDOM SUSTAINABLE DEVELOPMENT COMMISSION, *The Role of Nuclear Power in a Low Carbon Economy — Paper 4: The Economics of Nuclear Power*, prepared by Science and Technology Policy Research (SPRU, University of Sussex) and NERA Economic Consulting (March 2006).

[8] However, on a life cycle basis and in terms of generating costs, nuclear power plants are affected the least since they have the lowest specific material requirements per kW h generated.

[9] As of November 2008, the benchmark copper price had halved since September 2008 and world steel prices had fallen by almost 80% since July 2008.

The volatility of commodity prices has probably, in and of itself, also contributed to increased contingency allowances and thus higher cost estimates. The financial crisis may have had a similar effect.

Cost estimates may also have increased because, over the past few years, the global nuclear market shifted from a buyers' to a suppliers' market, a shift that generally exerts upward pressure on prices. The order books of vendors reached a level not seen since the late 1970s. Heavy forging capacity is limited, and lead times of more than 50 months are commonplace.

Another contributor to higher overall cost estimates may be the fact that the greater share of those estimates come from Europe and especially North America, where the lack of recent construction experience relative to Asia and new reactor designs likely contribute to the higher estimates shown in Fig. A-1.

Finally, as projects get closer to implementation, a greater proportion of recent cost estimates may reflect the cost conservatism of utilities more than the appraisal optimism of vendors and the technological optimism of some government and academic studies.

A.4.2. Safety[10]

Safety indicators, such as those published by the World Association of Nuclear Operators (WANO) and reproduced in Figs A-2 and A-3, 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 Agency's *Nuclear Safety Review for the Year 2008* (GC(53)/INF/2).

A.4.3. Human resource development

Estimates of the human resource requirements associated with any of the projections discussed in Section A.2 are not readily available. Moreover, 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.

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[10] 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/Anrep2008/) and at http://www-ns.iaea.org/.

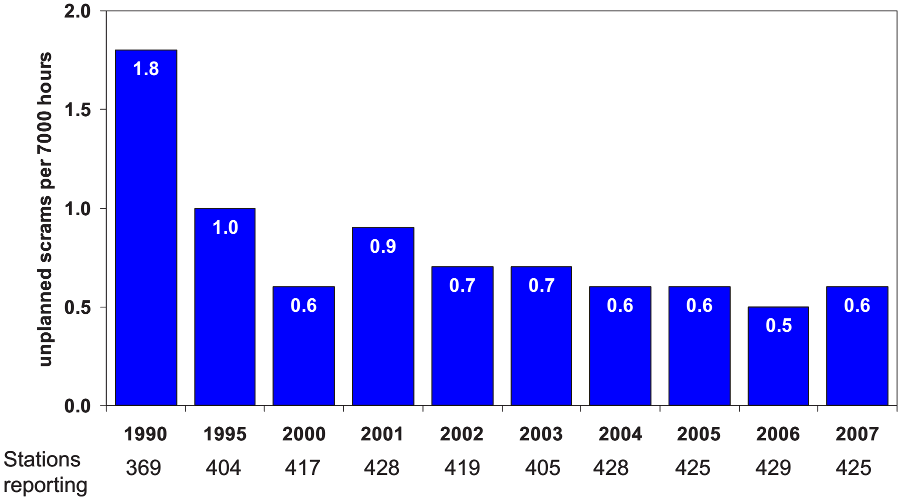

FIG. A-2. Unplanned scrams per 7000 hours critical (source: WANO 2007 Performance Indicators).

Concerns have been expressed in a number of countries about possible shortages of people with the skills needed by the nuclear power industry. An OECD/NEA report published in 2000 quantified for the first time the status of nuclear education in its member countries, noting that in most cases nuclear education had declined to the extent that expertise and competence in core

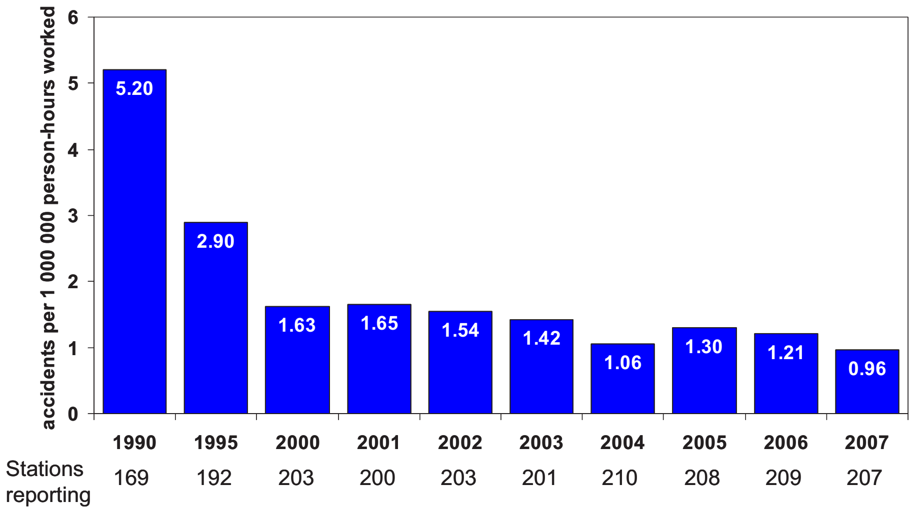

FIG. A-3. Industrial accidents at nuclear power plants per 1 000 000 person-hours worked (source: WANO 2007 Performance Indicators).

nuclear technologies were becoming increasingly difficult to sustain.[11] However, the OECD/NEA has also noted that the overall losses of technical competencies and skills varied from one country to another according to the strength of the nuclear power programme.[12] The paradoxical result is that concerns about manpower shortages appear to be expressed less often in countries with faster growing 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. Figure A-4 shows the increase in the number of graduates with nuclear engineering degrees in the USA, largely as a result of the University Reactor Infrastructure and Education Assistance Programme.

If the higher projections for nuclear power described in Section A.2 are realized, the success reflected in Fig. A-4 will have to be replicated several times over. That challenge will be significant, but not unprecedented. The Agency's high projection, for example, would require bringing online an

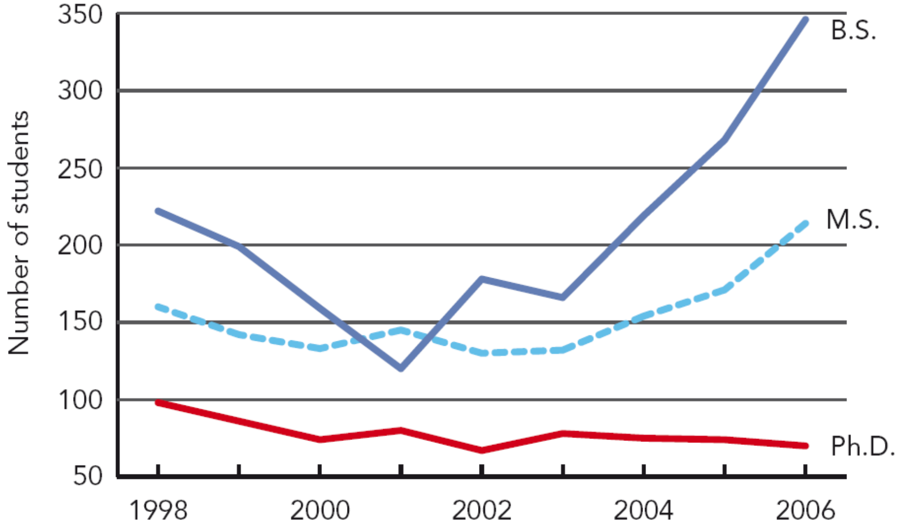

FIG. A-4. Nuclear engineering degrees at US universities (B.S. = Bachelor of Science, M.S. = Master of Science, Ph.D. = Doctor of Philosophy) (source: OECD Nuclear Energy Agency, Nuclear Energy Outlook 2008, OECD, Paris (2008)).

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[11] OECD NUCLEAR ENERGY AGENCY, *Nuclear Education and Training: Cause for Concern?* OECD, Paris (2000).

[12] OECD NUCLEAR ENERGY AGENCY, *Nuclear Energy Outlook 2008*, OECD, Paris (2008).

average of 17 new reactors each year, essentially the same as the annual average of 16 new reactors during the 1970s. Moreover, in the high projection, nuclear power's share of global electricity remains nearly constant through 2030, meaning that other electricity sources — and their manpower needs — would be growing at the same rate as nuclear power. The challenge faced by nuclear power is not exceptional.

A.4.4. Public acceptance of nuclear energy

The first issue in the Agency's guidance for countries considering the introduction of nuclear power[13] is labelled "national position": "The government should adopt a clear statement of intent to develop a nuclear power programme and communicate that intent locally, nationally, regionally and internationally." Comparable advice might equally be given in countries that already have nuclear power, and all governments supporting nuclear power should seek broad national support.

The most common way to find out whether there is broad national support for nuclear power to match the rising expectations discussed in Section A.2 is through public opinion surveys. However, these have their weaknesses. Responses can depend on how a question is phrased, and even experts may disagree on how some responses should be interpreted. Nonetheless, reputable techniques exist for eliminating bias from sample selection, from the phrasing of questions and from the interpretation of results.

Figures A-5 and A-6 present recent trends or, where no time series data were available, 'snapshots' of public acceptance of nuclear energy in countries already using nuclear power (Fig. A-5) and in a few countries without nuclear power (Fig. A-6). The value on the vertical scale, the public acceptance index (PAI), is the average of the surveys reviewed for a given country and year, normalized to a scale from 0 (complete rejection) to 100 (complete approval).

The PAIs in the countries that already have nuclear power programmes (Fig. A-5) are generally higher than the PAIs in those that do not (Fig. A-6).

Among the 12 countries with nuclear power programmes shown in Fig. A-5, public acceptance increased in 2008 in most cases. The two exceptions were Spain and Germany, which both have nuclear phase-out policies. The

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, *Milestones in the Development of a National Infrastructure for Nuclear Power*, IAEA Nuclear Energy Series No. NG-G-3.1, IAEA, Vienna(2007).

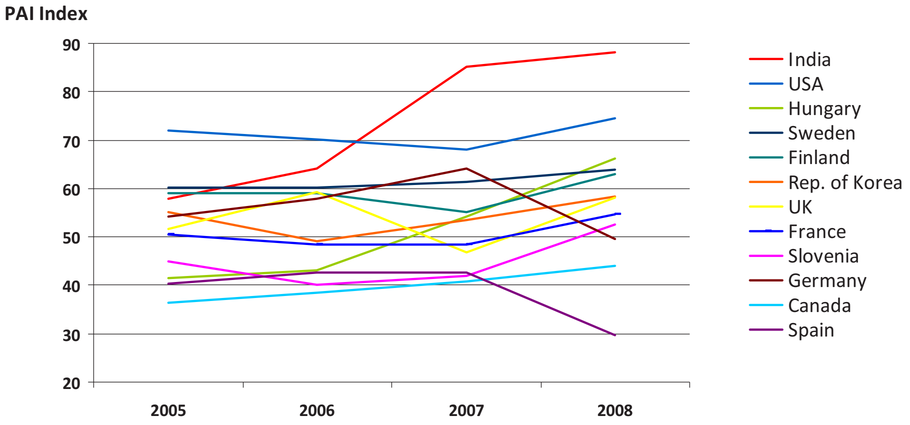

FIG. A-5. Public acceptance in a number of countries using nuclear power.

third country in Fig. A-5 with a phase-out policy, Sweden, shows stronger, more stable and slightly increasing support for nuclear power.

Of the seven countries without nuclear power programmes shown in Fig. A-6, five are considering starting or restarting nuclear power programmes: Egypt, Indonesia, Italy, Poland and Thailand. In these five, the PAIs are above or close to 50%.

The details of the surveys that were reviewed for Figs A-5 and A-6 contain insights, beyond those revealed in the figures' aggregate results that can help design public information programmes for specific situations. For example, the results for Hungary show a rather fast recovery from the low levels that public acceptance dropped to following a fuel cleaning accident in

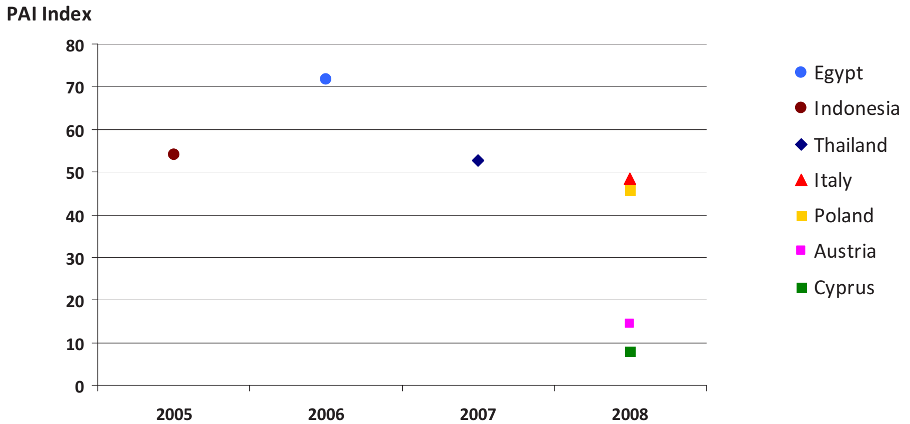

FIG. A-6. Public acceptance in a number of countries without nuclear power programmes.

2003. This suggests the importance to public acceptance of safe, incident-free operation of all nuclear facilities.

B. ADVANCED FISSION AND FUSION

B.1. Advanced fission[14]

B.1.1. Water cooled reactors

All six reactors on which China started construction in 2008 are 1000 MW(e) PWRs, an evolutionary design based on Generation II technology with modifications. The first Generation III PWR project, based on AP-1000 technology is moving smoothly, with construction starting in 2009.

In Japan, Mitsubishi Heavy Industries has developed a 1700 MW(e) version of the advanced pressurized water reactor (APWR) for the US market, the US-APWR, which started the NRC design certification process in 2008. The European version of the APWR, the EU-APWR, was submitted also in 2008 to be assessed for compliance with the European Utility Requirements.

In the Republic of Korea, construction started in 2008 on the first advanced power reactor, APR-1400, Shin-Kori 3.

In the Russian Federation, construction started on the first WWER-1200 units in 2008, Novovoronezh 2-1 and Leningrad 2-1. The contractor and site were changed for the first floating KLT-40S reactors (two reactors of 35 MW(e) each), on which construction began in 2007. Their target deployment date shifted from 2010 to 2012.

In 2008, the NRC design certification process was started for a US version of the European pressurized water reactor (EPR), and an application for a design certification amendment for the AP-1000 was initiated. New documents were submitted as part of the pre-application to the NRC for Westinghouse's 335 MW(e) integral PWR called IRIS.

In Canada, Atomic Energy of Canada Limited (AECL) is developing an advanced CANDU reactor (ACR) that incorporates very high component

[14] More detailed information on IAEA activities concerning advanced fission reactors is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2008/).

standardization and slightly enriched uranium to compensate for the use of light water as the primary coolant. In 2008, the Canadian Nuclear Safety Commission started the design review of the ACR-1000.

2.2. India has two 540 MW(e) heavy water reactors (HWRs) in operation. It is designing an evolutionary 700 MW(e) HWR and an Advanced Heavy Water Reactor (AHWR), which will use thorium with heavy water moderation, a boiling light water coolant in vertical pressure tubes, and passive safety systems.

B.1.2. Fast neutron systems

Component installation work was completed in 2008 for the 65 MW(th) (20 MW(e)) pool-type China Experimental Fast Reactor. Debugging activities are under way. Two hundred and fifty tonnes of nuclear grade sodium were shipped to the plant, and filling of the primary and secondary loops took place in April 2009.

The reactor vault for India's 500 MW(e) Prototype Fast Breeder Reactor (PFBR) at Kalpakkam was completed in 2008 and the safety vessel installed in the vault. The civil construction of the PFBR buildings that are part of the nuclear island is nearing completion. The thermal baffle, thermal insulation panels, sodium storage tanks, argon buffer tanks, core catcher and core support structure have been completed, and the main vessel is nearing completion.

Japan completed the refurbishment of the MONJU reactor and component testing. Most full system tests were also completed. Nonetheless, the scheduled restart was postponed from 2008 to 2009. Japan also launched a national Fast Reactor Cycle Technology Development Project to commercialize fast reactor technology.

In the Russian Federation, construction was completed on the foundation plates of the reactor compartment and the turbine hall for the BN-800 fast reactor at Beloyarsk. Commissioning is planned for 2012.

Belgium advanced the design work for the primary system, core design and plant layout of MYRRHA, a subcritical experimental fast reactor, to make it compatible with the EC project on an experimental accelerator driven system (XT-ADS). To test subcriticality monitoring, an experimental facility, GUINEVERE, is being built, coupling a continuous deuteron accelerator with a titanium–tritium target installed in a lead cooled, fast subcritical multiplying system. GUINEVERE is scheduled to be operational in March 2010.

B.1.3. Gas cooled reactors

The helium test facility, commissioned in 2007 for South Africa's pebble bed modular reactor (PBMR), made possible the first full scale operating tests on critical components of the reactivity control system, reserve shutdown system and the fuel handling system. In 2008, the South African National Nuclear Regulator granted a hot commissioning licence for the Advance Coater Facility at Pelindaba, allowing the project to start manufacturing fuel spheres.

In Japan, more rigorous tests of the High Temperature Engineering Test Reactor (HTTR), of 90 days in total with 50 days at 950°C, are scheduled to take place before the end of 2009. In 2007, a first 30 day full power test with the outlet coolant temperature at 850°C was completed, confirming improvements in the manufacturing of coated fuel particles.

In the USA, the Next Generation Nuclear Plant (NGNP) project reached a major milestone in 2008 by achieving zero fuel failures during long irradiation periods (9% burnup) in the advanced test reactor at Idaho National Laboratory. This is a major accomplishment in demonstrating tristructural–isotropic (TRISO) fuel safety. The next target is a burnup of 16–18% before September 2009.

In China, the implementation plan for the demonstration high temperature gas cooled reactor was approved by the State Council of the People's Republic of China. The project license is under review, and construction is expected to start late next year.

B.1.4. INPRO and GIF

The Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) completed an extensive manual on methods to assess innovative nuclear energy systems, *Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems*, which was published in early 2009 as IAEA-TECDOC-1575. One joint and six national assessment studies were completed using INPRO's methods to identify weak links in the development chain, i.e. priority areas in each case for further research and development. INPRO published a report in early 2009 on *Common User Considerations by Developing Countries for Future Nuclear Power Plants*, the drafting of which engaged 26 additional countries beyond INPRO's now 30 members. The Russian Government decided to provide, for the first time, multi-year support to INPRO for 2008–2012.

Through a system of contracts and agreements, the Generation IV International Forum (GIF) coordinates research activities on the 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). In 2008, China signed a ‘system arrangement’ to join in collaborative work on VHTRs. France, Japan and the USA are harmonizing work on prototype SFRs, including design goals, safety principles, system configuration, power level, fuel type, cost reductions through innovation, schedules and target dates for prototypes and associated infrastructures. Specific projects are under way on system integration, safety and operation, advanced fuel, balance of plant, and the ‘global actinide cycle international demonstration’.

B.2. Fusion

In February 2008, the ITER International Fusion Energy Organization (ITER Organization) formally applied for a construction permit to build the International Thermonuclear Experimental Reactor (ITER), an experimental fusion reactor, in Cadarache, France.

In October 2008, fifty years of international fusion research was commemorated at the 22nd IAEA Fusion Energy Conference (FEC 2008) in Geneva, Switzerland. FEC 2008 was held on the same premises as the second United Nations International Conference on the Peaceful Uses of Atomic Energy in 1958, at which time fusion was first declassified and opened for public discussion. A record number of over 500 scientific papers were presented at FEC 2008.

Also at FEC 2008, a cooperation agreement was signed by the Agency and the ITER Organization. The scope of cooperation includes exchanging information, analysing fusion’s contribution to future nuclear power scenarios, training, publications, organization of scientific conferences, research on plasma physics and modelling, and fusion safety and security. The agreement is designed to facilitate interactions between ITER parties and other Agency Member States that are interested in fusion research but are not members of ITER.

In addition to progress on ITER, fusion laboratories in Belgium, Brazil, Canada, China, the Czech Republic, the Islamic Republic of Iran, Portugal, the Russian Federation, Thailand and the United Kingdom are developing a research network of users of small fusion devices. The Agency participates and, among other things, coordinates small tokamak research through joint experiments to promote international collaboration, network planning and the education of young scientists.

C. ATOMIC AND NUCLEAR DATA

With rising expectations for nuclear power, progress on fusion and a new generation of fission reactors, a number of papers and talks at the International Conference on the Physics of Reactors (PHYSOR'08) highlighted the efforts under way, including at the Agency, to meet the need for new and updated fission and capture cross section data for actinides, the need to reduce uncertainties, and the need for data required to implement spent fuel recycling.

Issues of plasma–wall interaction in fusion reactors leading to dust particle formation and related safety issues of tritium retention, pyrophoric behaviour, handling and inhalation were discussed at a 2008 meeting of the Subcommittee on Atomic and Molecular Data for Fusion of the International Fusion Research Council (IFRC). It was recommended that the Agency initiate multinational coordinated research projects to study the size, composition and origin of dust and the spectroscopic, collisional and sputtering data for tungsten as a candidate material for fusion devices (see Fig. C-1 for an example of how such data are used). Further, in order to quantify the radiation damage to, and activation of, structural components of new fusion devices, there is a need to update and extend the Fusion Evaluated Nuclear Data Library (FENDL) that is used for design studies and benchmarking material properties relevant to ITER.

As part of the supercomputer support for modelling fusion devices that is being developed under the European Fusion Development Agreement, a centre for high performance computing for fusion was inaugurated in May 2009 at the Jülich Supercomputing Centre in Germany.

The direct irradiation of tumour sites in patients, using accelerator-produced charged particles, provides a high accuracy dose delivered to the target while sparing surrounding healthy tissue. Two new hadron-therapy centres will soon become operational in Heidelberg, Germany and Pavia, Italy. Recognizing the need for accurate data to design and plan patient treatment facilities, priority is being given to the establishment of coordinated international efforts to quantify and recommend updated charged-particle interaction data for medical applications.

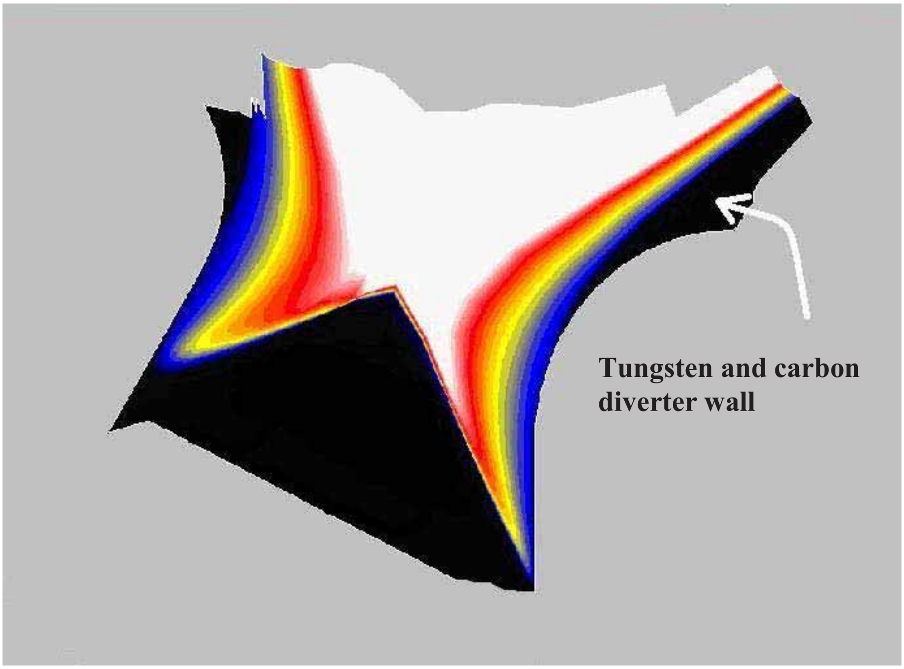

FIG. C-1. Computer simulation of the temperature profile of the diverter region of a fusion device. Temperatures range from ~ 200 000 (blue) to 1 000 000 (red) Kelvin, close to the temperature at the centre of the sun. Calculated with the B2-IRENE computer model (Research Centre Jülich), this study required voluminous reliable atomic and molecular data, many of which have been derived and assembled from a series of recent Agency coordinated research projects.

D. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

D.1. Accelerators

In developing countries, one important way to build competence in nuclear science is through the establishment of an accelerator facility, as well as its effective use for nuclear education and training, and hands-on experience in all related applications. To further broaden educational opportunities in developing regions, the Agency fosters international cooperation to leverage existing expertise and facilities, for example in South Africa, to benefit potential regional partners, for example Ghana and Nigeria.

Analytical methods developed at synchrotron radiation sources are increasing the understanding of novel and biological materials. New techniques developed using smaller conventional X ray sources are now being applied at synchrotrons like ANKA in Germany and will also be used at the Elettra facility in Italy. This approach makes use of the superior features of X rays available from synchrotron radiation and will thus increase analytic sensitivity and reliability.

Advances in ion beam technology and instrumentation are increasing the use of focused proton ion beams in biomedical research, particularly on the effects of radiation on living cells. The world's first vertical scanning focused nanobeam for basic research became operational in the United Kingdom in November 2008. It will provide new data on the radiation sensitivity of cancerous tumours, on processes that may lead to cancer, and on the risks of low level exposure to radiation. The new proton nanobeam will, for the first time, supply researchers with nanometre sized proton beams to target and irradiate specific locations in human cells with high precision. It will clarify the interactions between chemotherapeutic drugs and radiation, helping clinicians to test the efficacy of different cancer treatment strategies.

D.2. Research reactors

A major use of research reactors is to produce radioisotopes. In 2008, the unavailability of the few large ageing reactors used for isotope production posed problems and raised concerns about the security of radioisotope supplies (molybdenum-99 in particular) for vital medical and industrial applications. The new OPAL Reactor in Australia, which first achieved full power in 2006, is the only likely immediate addition to existing capacity. A number of national reactor centres are exploring, with the Agency, possible capacity additions through increased use of currently underutilized reactors. More information is provided in Section I on radioisotopes.

The first nuclear research reactor in Morocco, a TRIGA Mark-II type (2 MW), attained first criticality in May 2007; in June it achieved full power and in September 2007 it completed all required reactor testing. The reactor is located at the Maâmora Nuclear Research Centre (CENM), approximately 25 km north of Rabat. It uses LEU fuel and is designed for a planned future upgrade to 3 MW. The facility will be used for manpower training, isotope production, analytic services such as neutron activation analysis and non-destructive examination, and basic research in solid state and reactor physics.

Given the projected decrease in research reactors from 245 today to between 100 and 150 in 2020, greater international cooperation will be required to assure broad access to such facilities and their efficient use. To that end, the Agency has begun establishing a number of regional networks: Eastern European Research Reactor Initiative (EERRI), Caribbean Research Reactor Coalition (CRRC), Mediterranean Research Reactor Utilization Network (M-RRUN), and Baltic Research Reactor Utilization Network (B-RRUN). An additional Network on Residual Stress and Texture Analysis for Industrial Partners (STRAINET) is focused on a specific application rather than a region. These networks will also contribute to upgrading existing facilities, developing new facilities and improving access to countries without research reactors. The new Moroccan reactor will be open to both the national and international user community on a time sharing basis, and will further help regional collaboration, networking and research reactor coalitions.

The Reduced Enrichment for Research and Test Reactors (RERTR) Programme, under the Global Threat Reduction Initiative (GTRI), converts research reactors using high enriched uranium (HEU) fuel to low enriched uranium (LEU) fuel. By the end of 2008, 62 research reactors around the world that had been operating with HEU fuel were shut down or converted to LEU fuel, and another 39 are planned for conversion with existing qualified fuels. The RERTR Programme celebrated its 30th anniversary during its annual meeting held in Washington, D.C. in October 2008.

Very high density advanced uranium–molybdenum fuels that still need to be developed and qualified, will be required for the conversion of an additional 28 research reactors. Work began on such fuels in the early 1990s but encountered difficulties due to swelling of the reaction layer, which forms between the fuel and the aluminium matrix during irradiation. These are being investigated collaboratively by an International Fuel Development Working Group that includes Argentina, Belgium, Canada, France, Germany, the Republic of Korea, the Russian Federation and the USA. Substantial progress has been made on several fronts, but further progress and significant testing are still necessary to achieve the RERTR Programme goal of delivering a qualified fuel by the end of 2011.

E. NUCLEAR TECHNOLOGIES IN FOOD AND AGRICULTURE

E.1. Improving livestock productivity and health

Nuclear and related technologies help improve livestock productivity. Isotopes of carbon, hydrogen, sulphur, phosphorus or nitrogen are used to study the conversion and uptake of feed nutrients, and to evaluate the role of microbes in the rumen of livestock in feed utilization. Ruminants rely on these microorganisms living in their digestive tract to convert feed components into useable sources of energy and protein.

Identification and selection for desirable genetic characteristics, e.g. leaner meat, increased milk production or disease tolerance, can be done through the direct labelling of DNA. Isotopic labels are used to determine parentage or trace the origin of products, and help in assisting developing countries gain access to export markets.

Stable isotopes, as nature's 'ecological recorders', are useful in studying animal movement. The profiles of carbon-13 and nitrogen-15 can indicate the origin and breeding habitat of migratory birds, thereby enabling risk assessment and prediction of the spread of disease (e.g. avian influenza). Currently the most effective tracers are hydrogen isotopes found in metabolically inert, seasonally grown tissues, such as feathers and claws. Once the isotope profile of a particular bird population or ecosystem is established, any individual provides information on the global migration of that species or from that reference point. Global grids of hydrogen and oxygen water isotopes are constructed using the IAEA–World Meteorological Organization (WMO) Global Network of Isotopes in Precipitation (GNIP) database, and are compared with the feather profiles of migratory bird species in different locations to identify where feather growth occurred and thus trace the origin of migratory birds.[15]

[15] For further information on the IAEA's work in this area, please visit http://www-naweb.iaea.org/nafa/aph/index.html

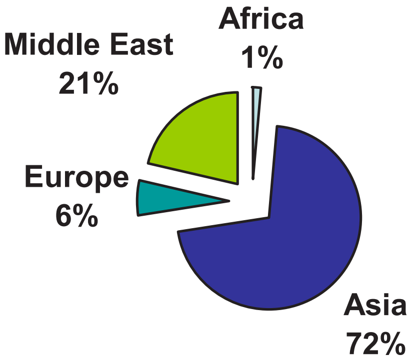

FIG. E-1. Geographical distribution of avian influenza (subtype H5N1) outbreaks in poultry from 2003–2008 (source: World Organisation for Animal Health (OIE)).

E.2. Vaccine research

Inactivation of pathogens by irradiation is revolutionizing vaccine research. Such treated vaccines stimulate a protective immune response similar to live pathogens, and are superior to that achievable by heat or chemical treatment. Irradiation opens up new possibilities for preventing diseases such as nagana, foot and mouth disease, fascioliasis and neospora in cattle, for which genetically engineered vaccines have been largely unsuccessful. Recent studies show that carefully administered doses of irradiation to alter the gene expression in pathogens have led to enhanced protection.

Good evidence for breed and individual genetic differences in resistance to infectious diseases provides an alternative means to address animal disease through the identification of genetic markers associated with such resistance. These methods involve the use of radiolabelled nucleotides in DNA hybridization such as DNA characterization, and radiation hybrid (RH) mapping procedures. The acquisition of genetic information for livestock species is crucial for harnessing the benefits of genetic variation for economically important traits. This process is greatly facilitated by the ordering of molecular markers along the selected chromosomes.

RH maps derived by radiation-fragmentation of chromosomes in hybrid cell lines can be tested for the presence of DNA markers or by comparative gene mapping to enable identification of candidate genes for specific traits. Although considerable progress has been made with bovine genome sequencing, the same cannot be said for sheep and goats. There is an urgent need for RH mapping of qualitative trait loci (QTL) correlated to disease resistance and productivity (milk production, and carcass and wool quality). By investing in these technologies, together with assays using phosphorus-32, sulphur-35, sulphur-35 methionine, and iodine-125, to monitor productivity and reproduction, it will be possible to improve performance.

E.3. Insect pest control

E.3.1. X ray irradiation for insect sterilization

Ongoing difficulties in obtaining and shipping isotopic irradiators have made it more pressing to evaluate X ray radiation as an alternative to gamma radiation. Work on adapting an RS2400 X ray irradiator for insect sterilization has advanced with an improved carousel system and new canisters made of carbon fibre reinforced resin incorporating steel filtration, resulting in an acceptable dose uniformity ratio (DUR) of less than 1.3. In addition, revising the control programme permits the selection of a predetermined amount of energy delivered to the insects.

Bioassays have been used to evaluate the relative effectiveness of both the X ray irradiation and gamma radiation systems on the quality of insects that are the target of the sterile insect technique (SIT). Fruit fly pupae of the same age were irradiated at the same nominal doses in either the X ray machine or a gamma irradiator and then assessed under the same conditions for comparative adult emergence, survival and sterility rates. Field cage tests on mating competitiveness between males treated with gamma rays and X rays were also carried out to assess the treatment differences under simulated field conditions. Dosimetric procedures conducted after treatment determined actual doses received by the pupae.[16] Preliminary data for *Bactrocera cucurbitae* (melon fly), *Ceratitis capitata* (Mediterranean fruit fly) and *Anastrepha fraterculus* (South American fruit fly), representing significant fruit fly pests in Asia, Africa and the Americas, on the level of residual fertility and normal adult emergence and behaviour suggest that there are no differences between gamma rays and X rays in each of the three species.

E.3.2. SIT against tsetse flies

Efforts to support African Member States with the transfer of SIT against tsetse flies are being pursued for priority areas. These include Ethiopia (*Glossina pallidipes*), KwaZulu-Natal in South Africa and Mozambique (*G.*

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[16] For information on and access to the database on insect sterilization, please visit http://www-naweb.iaea.org/nafa/ipc/index.html.

austeni and *G. brevipalpis*), and Senegal, where the government has a programme that aims at eliminating *G. palpalis* from the Niayes region located north-east of Dakar, which has a high livestock density.

In Senegal, entomological baseline data collection, which has allowed the development of accurate tsetse distribution maps with the aid of modern spatial tools, mathematical modelling and population genetics, has shown that the tsetse population in the Niayes region is completely isolated from the remainder of the tsetse belt. This offers an opportunity to create a sustainable tsetse free zone. Surveys show that SIT will be an essential component of an integrated approach; trial releases with sterile flies originating from Burkina Faso are planned for early 2009.

E.4. Food quality and safety

E.4.1. Traceability as an approach to control food contaminants and improve food safety

The use of agrochemicals such as pesticides and veterinary drugs is vital for agricultural production, especially given the need for increased productivity to respond to the current global food crisis. However, residues of these substances in food, and other natural and environmental contaminants such as mycotoxins and persistent organic pollutants, present risks to human health and may create barriers to agricultural trade. Global factors such as climate change and changing crop and livestock production practices also exacerbate food contamination problems.

Control of these hazards requires a holistic approach addressing the entire food production chain, which depends on the application of guidelines to minimize risks and feedback mechanisms to ensure the effectiveness of controls. An essential element of this approach is the ability to trace food products to their source — traceability — in order to facilitate corrective actions when contamination is detected. Isotopic techniques offer distinct advantages in this field and — when used in combination with conventional technology — can be applied to provide both robust traceability mechanisms and monitoring methodology for contaminants in food. Even where food safety is not a primary issue, the capacity to establish food origin and authenticity through the application of stable isotope ratio techniques may be important to exporting countries since there may be considerable added value to commodities from specific regions. Isotopic techniques can uniquely be used to examine environmental factors leading to contamination of food commodities, which is of growing importance given predicted rates of climate change.

Techniques for the comparative measurement of stable isotopes such as strontium have proven excellent tools for tracing the origin of a variety of food products. The relative abundances of strontium isotopes in plants are governed by the isotopic composition of strontium in the environment in which the plant grows. The strontium isotope ratios measured in the plant provide a 'fingerprint' of the place of origin. This has been demonstrated for both plant (for example, asparagus) and animal products, where the strontium isotope profile in milk is related to the locale where the cattle grazed. Other isotope ratios such as hydrogen/deuterium/tritium, nitrogen-14/nitrogen-15, carbon-13/carbon-12, and oxygen-18/oxygen-16 can be used in the same way, or to provide complementary data.

E.5. Crop improvement

Induced mutants with desirable characteristics play an important role in boosting the production of various food crops.[17] In recent years, rapid developments in molecular biology have led to the availability in the public domain of information relating to the genetic make-up of living organisms. In this 'genomics era', scientists are deciphering the genetic code of more and more organisms, including crops.

Of particular value is the application of methods that advance natural mutation, enhancing or suppressing genetic traits in order to produce improved crop varieties. Emphasis on mutation induction is shifting from the traditional broadening of the genetic base of crops for breeding to include molecular biology research, which has resulted in a considerable increase in scientific work involving induced crop mutagenesis.

The current trend for enhancing efficiency levels in mutation induction assisted breeding is to strategically integrate relevant aspects of novel biotechnologies in the processes. Two such strategies, one dealing with the rapid identification of the mutated parts of the genetic make-up for upstream research, and the other dealing with the seamless integration of biotechnologies in the generation and identification of mutants, are reviewed below.

[17] Additional information is available in relevant sections of the latest Annual Report (http://www.iaea.org/Publications/Reports/Anrep2008/), or at http://www.iaea.org/About/Policy/GC/GC53/Agenda/index.html.

E.5.1. Gene identification and function elucidation using induced mutants

The traditional strategy for induced mutation in crop improvement, known as 'forward genetics', involved the reconstruction of the roles of genes on the basis of observation of the modified characteristics of the mutants. With the availability of molecular biology information, it is becoming commonplace to work backwards, starting from the studies of the modifications at the molecular level and relating these modifications to altered characteristics in crops.

This newer strategy, known as 'reverse genetics', relies on the availability of populations of well characterized mutant stocks of major crops, e.g. rice, maize, barley and wheat. Protocols have been developed that permit significant scaling up of procedures to permit the simultaneous querying of thousands of mutants for mutations in target regions of the genetic make-up. Reverse genetics has become a critical tool in gene discovery and function elucidation.

E.5.2. Integrated technologies for enhanced mutation induction

Major aims in enhancing the efficiency of the routine application of mutation induction have included the generation of large mutant populations and the identification of the desired mutants in the shortest possible time. Advances in cellular and tissue biology, especially those that exploit the ability of each individual cell to give rise to a whole plant (a phenomenon known as 'totipotency') are permitting the rapid generation of large populations of mutants.

Tens of thousands of mutants can be grown under aseptic conditions in laboratory test tubes and, once DNA has been extracted from them, either tested for certain traits (e.g. resistance to a disease toxin, tolerance to salt) in the test tube, or queried for mutations in pre-determined parts of the genetic make-up using neutral molecular biology tools. Either way, the size of the population that gets evaluated in the field is significantly reduced. This saves time, as well as human and financial resources. Current research trends involve the assemblage of these tools for major crops into technology packages, enhancing the efficiency of mutation induction assisted breeding.

E.6. Sustainable land and water management

E.6.1. Understanding the role of microorganisms in soil quality and fertility under changing climatic conditions[18]

Microbial communities play a major role in soil fertility through the decomposition of crop residues, livestock manure and soil organic matter. These microbes are often affected by variations in rainfall and temperature patterns caused by climate change. Recent advances in the use of stable isotopes like carbon-13, nitrogen-15 and oxygen-18 as biomarkers to characterize microbial communities and their interactions with soil nutrient and organic matter processes, known as stable isotope probing (SIP), are important for soil–water–nutrient management.

SIP helps to understand the interactions between soil microbial communities, and their specific functions in soil carbon sequestration, soil organic matter stabilization, soil fertility and soil resilience, as well as the soil productive capacity for sustainable intensification of cropping and livestock production.

SIP involves the introduction of a stable isotope labelled substrate into a soil microbial community to see the fate of the substrate. This allows direct observations of substrate assimilation to be made in minimally disturbed communities of microorganisms. Microorganisms that are actively involved in specific metabolic processes can be identified under conditions that approach those occurring in situ.

E.6.2. Stable isotopic tracers to support the control of GHG emissions from agricultural lands

Nitrogen losses from chemical fertilizers, wastewater irrigation and manure can lead to water pollution. This can be minimized by best farm management practices through appropriate nitrogen fertilizer applications and by using riparian zones or permanently wet swales in the gullies of agricultural hill slopes to remove nitrates from surface and subsurface runoff. Nitrates moving through riparian and wet swales are subject to a soil microbial process that converts nitrates to nitrous oxide (N_2O) and dinitrogen (N_2). Nitrous oxide is a long-lasting greenhouse gas and potential ozone depleting gas. Recently, nitrogen-15 enriched nitrates have been successfully used to quantify not only

[18] Please see http://www-naweb.iaea.org/nafa/swmn/index.html for further IAEA work on soil and water management.

nitrate removal, but also N_2O and N_2 generation rates from permanently wet swales in agricultural catchments. With the use of nitrogen-15, wet swales have been found to be a source of N_2O emissions when NO_3^- nitrate concentrations are unlimited, but can effectively function as a N_2O sink when NO_3^- levels are low. These findings provide a balanced solution for the use of wet swales, between water quality goals (NO_3^- removal) and greenhouse gas emission controls (minimizing N_2O emissions) through the use of engineered bypass flows to regulate nitrate loadings to wet swales during high flow events. This enhances retention time as well as nitrate-limiting conditions without creating N_2O emissions. Without the use of nitrogen-15, agricultural planners and resource managers would not be able to differentiate N_2O and N_2 emissions from NO_3^- removal.

F. HUMAN HEALTH

F.1. Linkages between nuclear medicine imaging and the pharmaceutical industry

Imaging is increasingly used as a biomarker to assess new drug development. With clinical trials for drug development being undertaken more and more in developing countries, innovative approaches to the development of new pharmaceuticals are of key importance.

Imaging has a fundamental role in drug discovery and early development of clinical applications. In this regard, fluorodeoxyglucose (FDG), as well as positron emission tomography (PET) combined with computed tomography (CT), are effective not only for the diagnosis and staging of diseases but also for monitoring and quantifying treatment benefits. In drug development, this could translate into identifying and stratifying patients who are eligible for a clinical trial and then quantifying the results of treatment. The convergence of stratification and diagnosis, or quantification of treatment benefits in research as well as in clinical treatment is an important new development that has potentially great benefits for both the pharmaceutical industry and, ultimately, patients.[19]

[19] For frequently asked questions on PET and associated technologies, please see http://www-naweb.iaea.org/nahu/nm/faqanswers.asp#pet.

F.2. Application of nuclear techniques to support nutrition

The increasing prevalence of non-communicable diseases is leading to major health challenges. Industrialized countries as well as countries in transition are grappling with an increasing constellation of diseases including type 2 diabetes and cardiovascular disease. In contrast, developing countries are confronted by the coexistence of undernutrition and overnutrition. This is arguably the most important issue on the global health agenda and is further complicated by the HIV/AIDS crisis in many countries.

The most vulnerable population groups are pregnant and lactating women and their young infants. Recent technical developments have focused on addressing a missing link in infant nutrition and health, i.e. body composition assessment to better understand the quality of growth during infancy and its link with later development of chronic diseases. Nuclear techniques offer the much needed tools to assess body composition, in particular in the assessment of total body water by stable isotope techniques and bone mass by dual energy X-ray absorptiometry. These techniques offer the highest available standard of body composition assessment and are thus used to validate alternative techniques such as bioelectrical impedance analysis.

Early in life, the structure and function of the body determines both short and longer term health outcomes. The ‘windows of opportunity’ during which the biology of physical growth and health status can be influenced by nutrition (either positively or negatively) include crucial times of rapid growth and during development of the foetus, as well as during the infant's first two years of life. Nutrition interventions during these ‘windows’ provide the best opportunity for the prevention of longer-term consequences of early undernutrition, including those deriving from intrauterine growth restriction and stunting. There is an urgent need to develop effective strategies to intervene during this crucial time to counteract the later development of chronic diseases. [20]

[20] To assist Member States in determining nutritional levels, a Vitamin A Tracer Task Force was initiated by the IAEA, USAID, HarvestPlus and ILSI to prepare documents on the appropriate use of vitamin A tracer (stable isotope) methodology and a handbook on vitamin A tracer dilution methods to assess the status and to evaluate intervention programmes.

F.3. Advances in quantitative imaging and internal dosimetry for nuclear medicine

The long-sought quest for a 'magic bullet', where an accurately targeted substance kills cancer cells without damaging healthy tissue, is progressively, albeit slowly, becoming a reality in therapeutic nuclear medicine. The principle has been successfully demonstrated for over 50 years using the radioisotope iodine-131 for the treatment of various thyroid diseases. Today, more sophisticated substances have been bioengineered to target a wider range of diseases. A few of them are approved for clinical use, while many more are currently being tested in clinical trials, some with the direct involvement of the Agency. A key aspect in evaluating the efficacy of these new radiolabelled compounds is to quantify the distribution and determine the radiation absorbed dose delivered to the disease site, but also to critical healthy tissue.

Nuclear medicine images typically are used for either detection tasks, such as identifying perfusion defects, or quantitative tasks, such as calculating left ventricular ejection fraction, standardized uptake values, or organ absorbed dose.[21] Over the past 15 years there has been a great deal of progress in the development of methods for accurately quantifying nuclear medicine images. However, propagation of these methods into clinics has been slow and as yet there are no standardized methods for quantifying single photon emission computed tomography (SPECT) or PET data.

Obtaining images that are suitable for quantitative tasks often requires additional processing compared to those used for visual interpretation. This additional processing frequently results in improved resolution and contrast and reduced artefacts (Fig. F-1). These improvements in the image can often, but not always, translate directly to improved performance of detection tasks. Another advantage of using such images is that they may provide improved measurement consistency for the field, minimizing variability across imaging centres, imaging equipment, scan protocols and patients.

F.4. Improvement in radiation oncology applications

Combined modality therapy (surgery, radiotherapy, chemotherapy, targeted drug treatment) improves survival in most common cancers. Advances in external beam radiotherapy have increased the accuracy requirements for dose delivery to patients. The three-dimensional conformal radiotherapy (3D-

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[21] Additional information is available at http://www.iaea.org/About/Policy/GC/GC53/Agenda/index.html.

CRT) approach is regarded as the standard in most indications of curative radiotherapy, and in many centres a substantial number of patients are treated with intensity modulated radiation therapy (IMRT).

Volumetric modulated arc therapy, combined tomography-therapy innovations, dose-individualized stereotactic body radiotherapy, and four dimensional image-guided radiotherapy (IGRT) (which expands the target volume to encompass the range of tumour motion) are being introduced into clinical practice. They enable the highest conformity and superior critical-structure sparing when the dose to adjacent normal tissue is minimized. Improved software for recording and verifying quality systems has become available to improve the process in clinical radiotherapy.

Increasingly, proton centres are being established to develop normal tissue-sparing high precision applications. In most cases, more evidence is needed to prove the superiority of these approaches compared to conventional radiotherapy.

In addition, information technology has brought about changes in the working methods in radiation oncology. Worldwide, the introduction of nationwide registries of case records and electronic patient files at the hospital level is developing rapidly.[22]

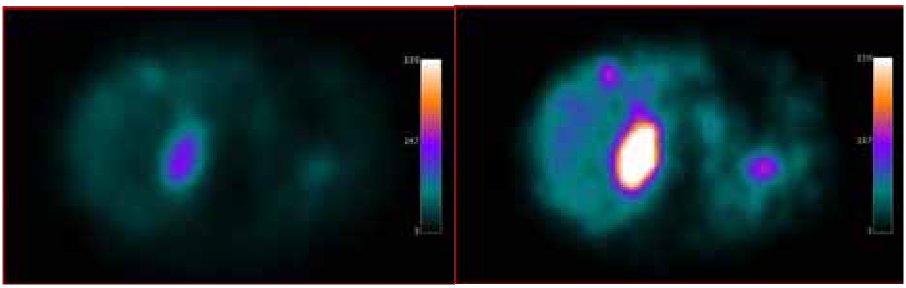

FIG. F-1. Iodine-123 metaiodobenzylguanidine (I-123 MIBG): transaxial section of upper abdomen in patient with recurring phaeochromocytoma. The left image shows the original SPECT image. The right image is corrected using CT acquired data on tissue density. This type of SPECT image correction can provide better diagnostic information and serve to more accurately quantify the uptake of the radiopharmaceutical (courtesy of the University of Pisa Medical School, Italy).

[22] At the IAEA's international conference on Advances in Radiation Oncology, held in April 2009, the Agency encouraged the world's leading manufacturers of radiation oncology equipment to produce more robust, less costly and portable radiation oncology equipment, for use in poor and rural settings.

G. ENVIRONMENT

G.1. ‘Hot particles’ in the environment

When assessing radiation doses and the impact of radiation on the environment, released radioactive particles play an important role. ‘Hot particles’ are small, radioactive objects containing a significant number of radionuclides with sometimes very high radioactivity. Originating from several possible sources including nuclear weapons tests, releases from the nuclear fuel cycle, and accidents involving nuclear material, hot particles contain considerably higher radioactivity levels than the bulk material or the population of other particles dispersed from these sources.

The properties and environmental behaviour of the particle-bound radionuclides are governed by their composition and the matrix structure, both factors being source term related and release scenario dependent (Figs G-1 and G-2). Mobility, environmental behaviour, bioavailability, and ecological and health effects of the radionuclides are basically determined by the properties of the particles such as microstructure, chemical composition and speciation. Although little information is presently available on the impact of hot particles on the environment, this will become more important as new techniques become available to characterize such particles.

Due to their small size, often in the range of a few micrometres and below, airborne hot particles are difficult to isolate. A new simple method has been developed for the manual manipulation and isolation of single particles in the size range of 1 μm and above using a light microscope and for even smaller ones directly within a scanning electron microscope (Fig. G-1). Once isolated, a particle can be examined using a variety of techniques which can be applied on a microscopic scale such as scanning electron microscopy, alpha particle detection, laser ablation inductively coupled plasma mass spectrometry (ICP–MS) and other mass spectrometry techniques, as well as X ray microtomography.

G.2. On-line access to worldwide marine radioactivity data

Containing over 110 000 data entries, the main objective of the Marine Information System (MARIS) (http://maris.iaea.org) is to provide easy access to marine radioactivity data. Furthermore, MARIS is an international

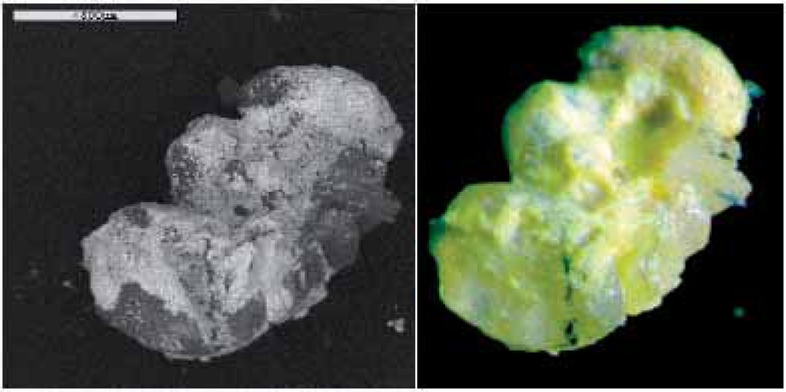

FIG. G-1. Scanning electron microscopy (SEM) (left), and light microscope (right) micrographs of a sand grain illustrating the shape and coverage of the particle with depleted uranium originating from a munition storage fire in Al-Doha, Kuwait. Scale: 500 µm (from LIND, O., Characterization of radioactive particles in the environment using advanced techniques, Thesis, Norway (2006)).

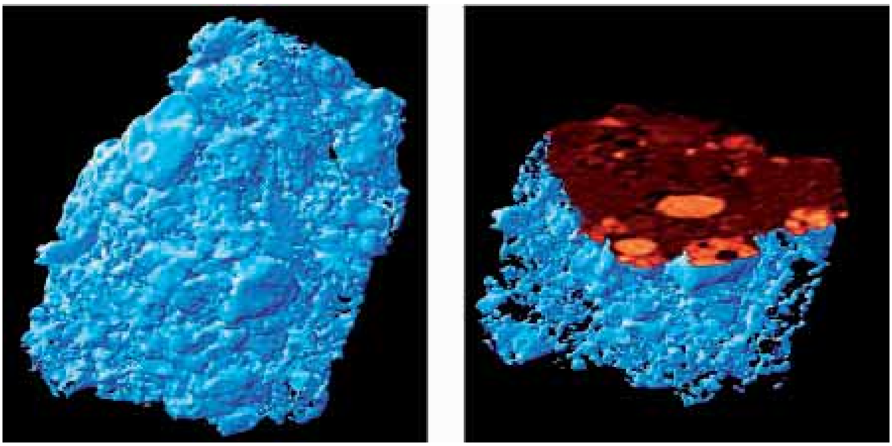

FIG. G-2. Microscopic X ray absorption tomography of an oxidized fuel particle released during the fire that followed the explosion in the Chernobyl reactor accident. 3-D rendering of tomographic slices showing the surface of the particle (left) and computerized (virtual) slicing of the 3-D image, exposing its heterogeneous inner structure (right). Particle width: about 300 µm (from SALBU, B., et al., "µ-XAS tomography and µ-XANES for characterization of fuel particles", ESRF Highlights 1999, European Synchrotron Research Facility, Grenoble (2000)).

reference source on radionuclide levels and trends in the marine environment, against which any further contributions from eventual releases to the marine environment can be evaluated. MARIS has provided policymakers in coastal regions with improved data for decision making.

MARIS contains past and present radioactivity data on the most significant anthropogenic and natural radionuclides in the world's oceans and seas, in deep basins, coastal zones and seawater, as well as in particulate matter, sediment and marine biota. These data originate from published scientific papers, reports and databases developed within institutes or scientific programmes in Member States.

The data in MARIS are used in baseline studies for the evaluation of levels, inventories and trends of radionuclides in the marine environment; for environmental impact assessments; and for the assessment of doses from marine exposure pathways. Together with oceanographic data, MARIS data are used to better characterize ocean currents, water column processes and sediment dynamics, and to study the fate of contaminants in the marine environment using radionuclides as analogues. MARIS data are also used to validate regional and global scale circulation and dispersion models which are useful, for example, for the prediction of climate change and ocean acidification.

G.3. Stable isotope labelling in marine food web studies

Stable carbon isotope compositions are widely used to study the sources of organic carbon in ecosystems and their use in the food web. Understanding the transfer of carbon and nutrients between the environment and marine organisms is key to enhancing knowledge on biogeochemical cycles and ecosystem functioning. The deliberate addition of a tracer such as a carbon-13 labelled compound under controlled conditions, and its tracking through the various components, provides valuable information. This can reveal which pathways are significant for identifying the role of important organisms within the ecosystem. Figure G-3 sketches the delta carbon-13 ($\delta^{13}C$) distribution in the environment. Through the analysis of lipid biomarkers characteristic of certain groups of organisms and the presence of isotope-signatures in these substances, it is now possible to resolve species-specific interactions using stable isotopes at the molecular level. In combination with mathematical modelling, such data may also be used to estimate the production and turnover rates of photosynthetic products from different marine organisms. The Agency is helping Member States to trace the transfer of carbon-13 labelled and non-labelled compounds through marine food chains, such as corals, plankton and bacteria based on the analysis of isotopic ratios of specific compounds by gas chromatography–isotope ratio mass spectrometry (GC–IRMS). The application of this newly developed nuclear technology would contribute to a better understanding of food web interactions and carbon cycling in the marine environment.

G.4. Radiotracers to measure impacts of ocean acidification on marine biodiversity in the Arctic and Mediterranean

Modelling studies have clearly identified that polar regions are particularly susceptible to the combined climate change effects of increasing temperature and ocean acidification. To better predict their impacts on marine biodiversity, the Agency has developed portable experimental facilities to study ocean acidification. This is being used with the calcium-45 isotope to measure rates of calcification in sea butterflies and cockles from the Arctic that are key foods of resident whales, walruses and seabirds. Under experimental exposures that replicate the acidified conditions predicted in the future for Arctic waters, the Agency has supported Member States in their determinations of appreciable reductions in calcification rates in sea butterflies by factors that are similar to those already measured for reef-building corals.

The Agency is helping Member States to carry out radiotracer studies on commercial fish, cuttlefish and octopus of the Mediterranean Sea to determine

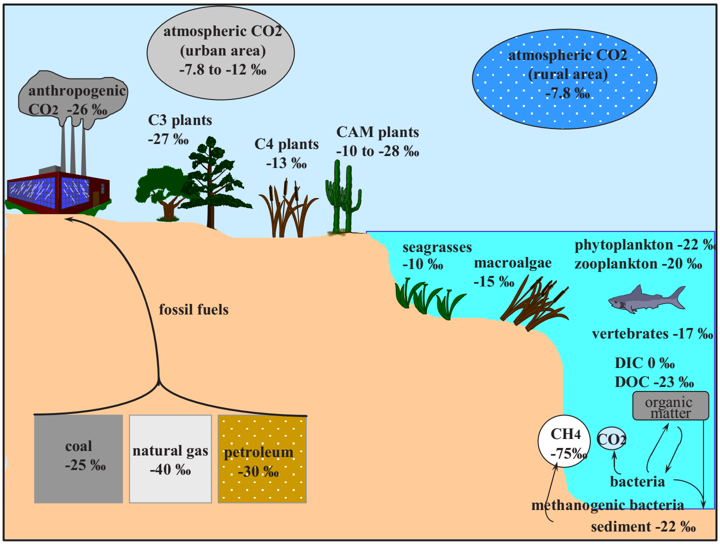

*FIG. G-3. Sketch of $\delta^{13}C$ distribution in the environment (modified after Tolosa, Oceanis **30** 2 (2004). 239–259). (CAM: crassulacean acid metabolism; DIC: dissolved inorganic carbon; DOC: dissolved organic carbon.)*

impacts of ocean acidification on their early life stages. This will further contribute to understanding and predicting to what extent ocean acidification will alter marine resources and the socioeconomic impact of these alterations.

H. WATER RESOURCES

In addition to population and economic growth, climate variability and change are significant drivers of stress on freshwater resources. Nearly one in three people on earth depends upon water from rivers that are fed by glaciers and snow melt. Increased variability and vulnerability of river flows in a warmer climate (due to increased melt-flows and changes in precipitation patterns) will drive a need for changes in water use and management practices. As development drives the need for greater renewable and non-renewable energy production, water for energy will also be an important consideration in water resources planning. Management responses to increased demands for freshwater resources would likely include a greater dependence on already stressed groundwater resources.

Yet there is a significant gap in our understanding of the distribution and renewability of groundwater resources. One notable effort in improving groundwater assessment is the Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP) (http://www.whymap.org/). This collaborative effort between the Agency's water resources programme, UNESCO's International Hydrological Programme (IHP), the German Federal Institute for Geosciences and Natural Resources (BGR), the International Association of Hydrogeologists and others was initiated in 1999 with the objective of collecting, collating, and visualizing hydrogeological and groundwater information on a global scale. The groundwater resources map (Fig. H-1), which was presented in 2008 at the 33rd International Geological Congress in Oslo, describes three main types of groundwater occurrences: in major basins with regional aquifers (shades of blue); in areas with complex hydrogeological structure (shades of green); and in areas with local and shallow aquifers (shades of brown). The shading of each colour represents the groundwater renewal or recharge rates. A regional groundwater resources map for southern Asia is shown in Fig. H-2.

Isotope methods help to easily identify aquifers which contain old water (and no or negligible recharge) and those with modern water (and significant recharge.)[23] When old groundwater is used for irrigation or for domestic or industrial water supply, it is described as 'mining' as the extracted groundwater will not be replaced naturally under current climate conditions. Such aquifers need to be managed much more carefully than aquifers that receive modern recharge. Mining of aquifers occurs in many countries around the world.

The availability of sound assessments of water resources, including groundwater, will help to substantially increase water availability. National assessments will improve the ability of countries to better use their regionally shared resources through improved strategic action programmes. The Agency is planning to launch a partnership to leverage its technical strengths and complement the mandates and activities of other agencies, such as the World Bank, UNDP and WMO, in order to develop a model scientific approach for water resources assessment that may be replicated in many Member States. This partnership effort, I-WAVE (IAEA-Water Availability Enhancement), will establish a comprehensive approach for water resources assessment, including surface and groundwater resources, as well as help develop better strategies for adaptation to climate change.

I. RADIOISOTOPE PRODUCTION AND AVAILABILITY

The global demand for radioisotope and radiation sources is increasing as a result of their use in medicine and industry. The 6th International Conference on Isotopes held in May 2008 in Seoul, the Republic of Korea, underlined the high demand for further developments and international cooperation. A World Council on Isotopes (WCI) is being developed to provide an appropriate forum for all stakeholders to facilitate the sustainable and safe production and application of radioisotopes.

The production capacity of radioisotopes using cyclotrons has increased. The number of regional centres for the production of clinical radiotracers for PET imaging is also growing. In response to growing demand for fluorodeoxy-glucose (FDG), tabletop cyclotrons (~7.5 MeV), together with advanced radiotracer synthesis modules based on microfluidics, are under development and are expected to be adopted by major hospitals worldwide. In addition, as

[23] Additional information is available in relevant sections of the latest IAEA Annual Report (http://www.iaea.org/Publications/Reports/Anrp2008).

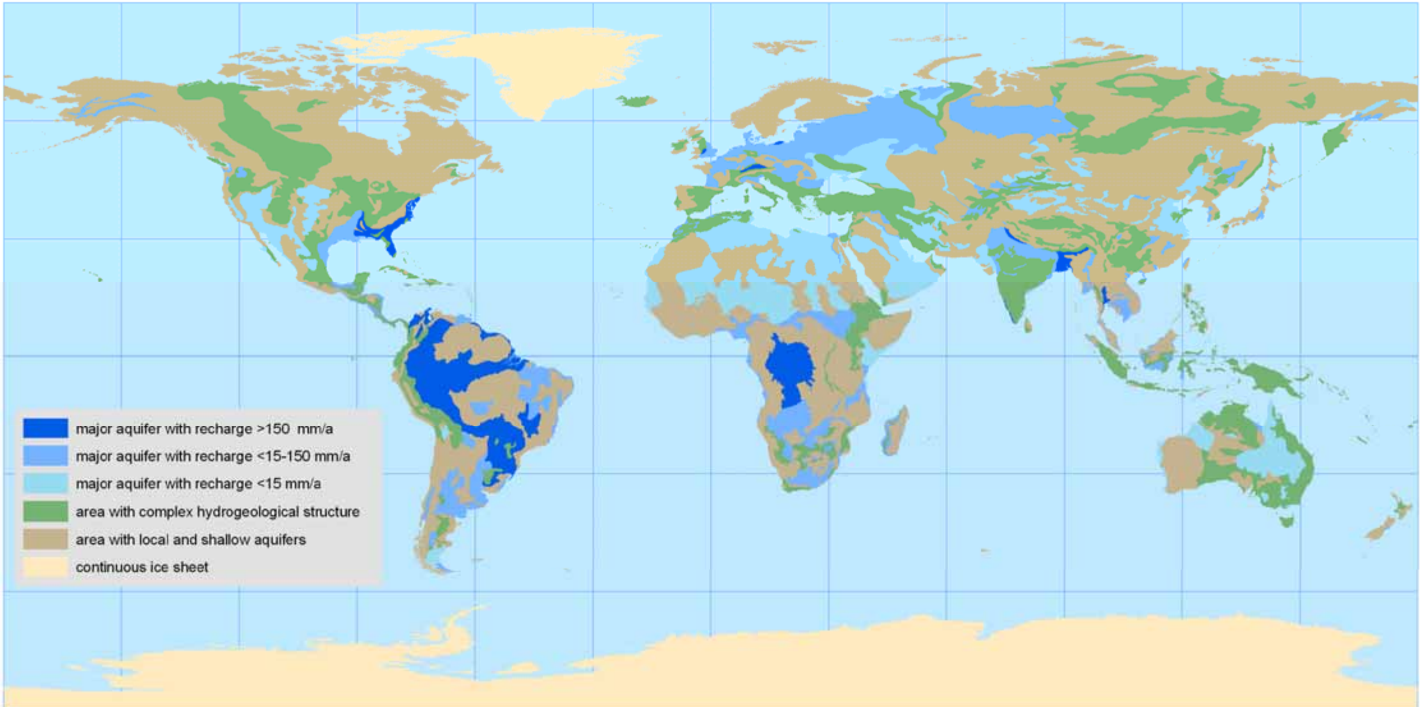

FIG. H-1. Groundwater resources of the world, WHYMAP (1:50 000 000 scale). Blue areas are groundwater systems in major basins; green areas represent groundwater systems with complex hydrogeological structure; and brown areas represent locations with local and shallow aquifer systems. The shades of the three main colours reflect groundwater renewal (recharge) rates.

some PET tracers have a higher specificity for imaging cancer, they are increasingly preferred over FDG, which also accumulates in sites of infection.

The growth in the number of PET and PET-CT centres has increased the utility of generator based PET tracers for superior imaging. For example, gallium-68, prepared from germanium-68, is used for the diagnostic imaging of cancer, and rubidium-82, prepared from strontium-82, is used for myocardial perfusion imaging.

Radionuclide therapy is experiencing a growth due to advances in targeting based on molecular nuclear medicine principles. Correspondingly, the demand for therapeutic radionuclides is expected to grow significantly. An electrochemical generator methodology developed for the preparation of high purity yttrium-90 (facilitated through an Agency coordinated research project) is expected to increase the availability of yttrium-90 based on a process amenable to remote safe operation in a module. Lutetium-177 is projected to become as important as iodine-131, and several countries have already begun or are planning medium to large scale production of this radioisotope.

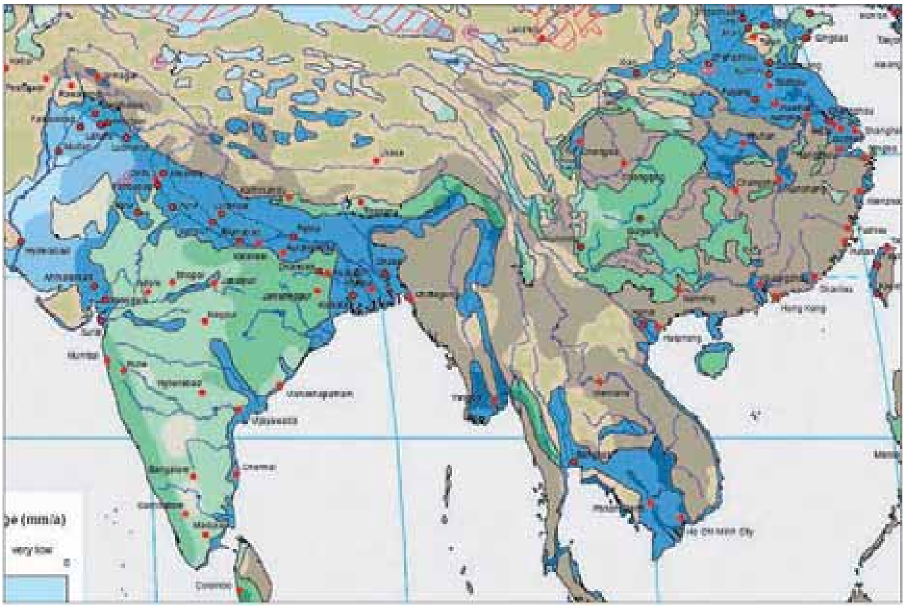

FIG. H-2. Detail of a 1:25 000 000 scale groundwater resources map showing southern Asia. Blue areas are groundwater systems in major basins; green areas represent groundwater systems with complex hydrogeological structure; and brown areas represent locations with local and shallow aquifer systems. The shades of the three main colours reflect groundwater renewal (recharge) rates.

I.1. Security of supplies of molybdenum-99

During the past year, disruptions in the supplies of the radioisotope molybdenum-99 — the source of widely used technetium-99m for diagnostic imaging — caused delays in patient services in nuclear medicine centres around the world. Molybdenum-99 requirements (about 450 000 GBq per week) are normally met by irradiation in five reactors located in Belgium, Canada, France, Netherlands and South Africa, and processing by four industrial facilities. More than 95% of all molybdenum-99 is produced using HEU targets. In January 2009, the US National Academy of Sciences, under Congressional mandate, released the report of a feasibility study on using LEU targets.[24]

The limited numbers of reactors that produce molybdenum-99 are all aged and due for maintenance shutdowns, which has led to problems in more than one production site. In August 2008, one reactor restart (in Petten, Netherlands) following a maintenance shutdown was delayed because of an unexpected technical problem. This occurred concurrently with the scheduled maintenance shutdown of two other reactors in Europe, as well as a radiological incident in a processing facility, leading to significant molybdenum-99 shortages in Europe and other regions. Concerns about the security of supplies of molybdenum-99 and other reactor based radioisotopes were compounded by the May 2008 termination of the MAPLE reactor project in Canada, and the realization that no new reactors are likely to start production until at least 2015.

The earliest additional large scale source of molybdenum-99 will likely come from the Australian Nuclear Science and Technology Organisation (ANSTO). In the USA, the University of Missouri Research Reactor (MURR) has made considerable progress in preparatory planning and exploring resources for becoming a domestic US producer with a target of meeting 30–50% of demand, although it would take three to four years after approvals to be established. Two other new facilities are being installed, in Egypt (supplied by INVAP, Argentina) and in Pakistan (supplied by Isotope Technologies, Germany), for the production of molybdenum-99, but exact production plans are yet to be announced.

There is an urgent need to expand geographically well distributed reactor irradiation capacity as well as to increase the number of processing facilities for the production of molybdenum-99. Governmental support and stronger cooperation among isotope manufacturers, including public–private partner-

[24] http://www.nap.edu/catalog.php?record_id=12569.

ships, will be required to ensure that suitable reactors will be engaged to irradiate LEU targets for molybdenum-99 production.

I.2. Electron beam processing

High-current electron beam (EB) accelerators are used in diverse industries to enhance the physical and chemical properties of materials (Fig. I-1) and to reduce undesirable contaminants. There are more than 1400 high current EB units in commercial use providing billions of euros of added value to numerous products. This is in addition to the nearly 1000 low current accelerators used for research purposes.

With the advent of high-energy (5–10 MeV) and high power (up to about 700 kW) EB accelerators, conversion of electron beam power to X radiation is now a commercially viable alternative to the industrial use of gamma rays. Figure I-2 shows containers that are capable of holding food products, such as cartons of ground beef or boxes of medical disposables, ready to be conveyed before two metre high water cooled tantalum X ray targets.

While the use of low energy (less than 500 keV) EB accelerators for the curing of inks, coatings and adhesives for the elimination of volatile organic compounds is growing, there is a need for mobile EB facilities for applications such as industrial wastewater treatment, seed disinfestation, and air deodorizing. An emerging area for low energy electron beam accelerators is surface decontamination, e.g. for PET bottles and packaging for aseptic filling.

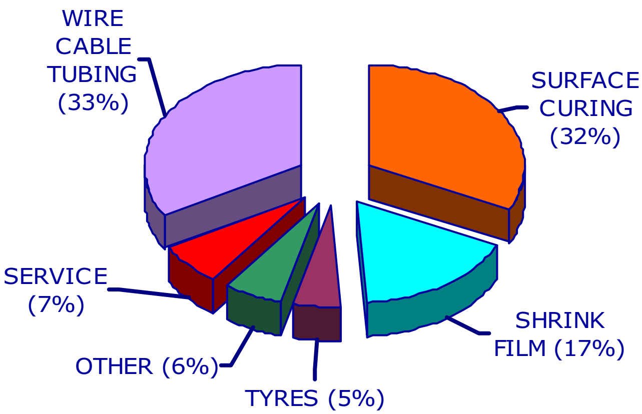

FIG. I-1. Typical pattern of industrial electron beam accelerator end-use markets. The bulk of the use is for cables, heat shrinkables and surface treatment (over 80%), while applications for medical devices and food products are envisaged to increase in the future.

I.3. Radiation processing in nanoscience

Radiation technologies can be used for the creation and characterization of new materials at the nanoscale. Radiation techniques are essential to nanotechnology because the beam can be focused into a few nanometres and scanned with high speed. A new technology has been demonstrated in the Netherlands: multiple electron beam mask-less lithography, which uses up to 13 000 parallel electron beams to directly write electronic circuit patterns on wafers, eliminating the need for masks. This technique couples very high resolution and depth of field of the electron beam with high throughput, providing a cost effective way of making the next generation of chips.

Low energy ion beam lithography works in a similar manner to electron beam lithography, with advantages such as minimal scattering and nearly uniform energy loss along the trajectory. A new method was recently developed using a variable size aperture which shapes the beam spot on the

FIG. I-2. Containers with materials (e.g. medical disposables, food products) moving for processing by X rays from 5–7.5 MeV electron beams.

sample. By combining different sizes of the aperture with different positions of the sample, complex structures can be exposed in a short time. A heavy ion beam with acceleration energy of more than 1 MeV can be used for fabrication of ion-track membranes from polymers and in turn used as a template for the synthesis of microstructures and nanostructures in the form of wires. Magnetic, conducting and superconducting nanowires and nanotubules, single or in array, have been manufactured this way. As well as in the electronics industry, electron beam and ion beam technologies are used as tools for investigating physical phenomena at nanoscale dimensions to support research in physics, nanophotonics, nanobiotechnology and nanobiomedicine.

Annex I

DEVELOPMENTS IN MUTATION ASSISTED PLANT BREEDING

I-1. Introduction

Spontaneous mutation, the naturally occurring heritable change to genetic material which played a pivotal role in biological evolution and formed the basis for speciation and domestication of both crops and animals, can be artificially induced and supports the maintenance of biodiversity. Since the discovery of X ray and other forms of radiation at the end of the 19th century and the ensuing demonstration of the ability of these forms of nuclear energy to alter genetic material, scientists have routinely used different types of ionizing radiation to create variants of crops [I-1].

There have been more than 2700 officially released mutant varieties from 170 different plant species in more than 60 countries throughout the world (Fig. I-1) that not only increase biodiversity, but also provide breeding material for conventional plant breeding, thus directly contributing to the conservation and use of plant genetic resources. Hundreds of millions of hectares of higher yielding or more disease resistant crops have been developed annually through induced mutations and released to smallholders. These mutant varieties enhance rural income, improve human nutrition and contribute to environmentally sustainable food security in the world. Close to 90% of these officially

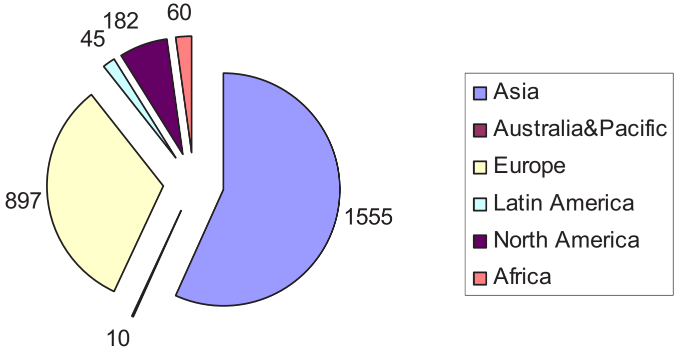

FIG. I-1. Number of mutant varieties developed in different regions of the world (FAO/IAEA Mutant Varieties and Genetic Stock Database http://mvgs.iaea.org/).

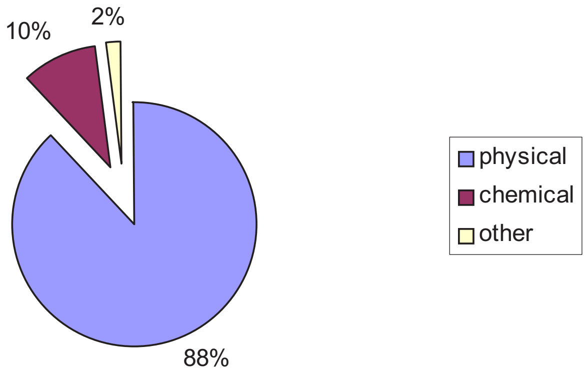

FIG. I-2. Comparative use of different types of mutagens. The majority of mutant varieties are developed through irradiation (e.g. fast neutrons, X rays, and more than 64% through gamma irradiation).

released mutant varieties were produced using radiation (Fig. I-2) and contribute billions of dollars of additional income to farmers annually [I-2].[25]

Since the early 1980s, there has been a surge in the applications of recombinant DNA technologies in the quest for answers to several biological questions in health, agriculture and industry. This has brought about an unprecedented escalation in the volume of information on the 'building blocks' of heredity (i.e. DNA sequence information), which is now available in the public domain. The DNA sequences of many organisms including the human organism (e.g. the human genome project) and several crop species have been published. This is referred to as the genomics era, a term coined to reflect the availability of information spanning the total genetic make-up of an organism, the genome. The next goal in genomic studies is to unlock information contained in the genomes of humans, animals, and plants, identifying and ascribing functions to those parts of the genetic make-up; this will have far reaching scientific implications and commercial potential. At the same time, various molecular and genomic tools and techniques have been developed and have substantially transformed the landscape of biological research. Efforts towards crop improvement have also entered this new era, increasingly using

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[25] The IAEA, through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agricultue, is working in partnership with national agricultural authorities, farmers, and global research institutes such as the International Rice Research Institute (IRRI) headquartered in the Philippines, to introduce new mutant varieties of wheat, rice and cassava species, in order to increase agricultural efficiency, particularly in marginal lands featuring drought and poor soil fertility.

both genomic knowledge and various molecular tools. Coinciding with these developments, an expansion in the research and application of induced mutations for crop improvement has also taken place in scientific communities throughout the world.

Mutation induction continues to contribute to crop improvement, using physical mutagens such as gamma ray, X ray, fast neutron, and chemical mutagens such as EMS (ethyl-methane-sulphonate) and sodium azides. Recently, new physical mutagens, such as ion beam radiation and cosmic rays, have been proven to be effective for inducing mutations.

Below is an overview of recent developments related to plant mutation breeding; induced mutations for harnessing genomics resources; bio-/molecular technologies for enhancing the efficiency of mutation induction and utilization; and ion beam radiation as a novel mutation induction technique.

I-2. Mutant stocks as gene repositories

Generations of induced mutants have long been driven by plant breeders, who would then use them directly or indirectly (through further cross-breeding) in the process of developing new varieties. The plant breeder's ability to improve a crop is as good as the available genetic variation, which can be exploited in cross breeding and other forms of selection. Mutation induction offers the possibility to induce such variations where the desired genetic variation is lacking. Since the genomic region critical for a trait, known as the gene, can be identified by the deductive process of inducing a series of mutants, identifying which traits have been modified and relating such observed modifications to changes in genomic regions of such mutants compared to the 'normal' types is important. The mutated genomic region that exerts control over the trait in question is therefore identified as the gene responsible for the expression of the trait. The mutant genetic resources as one of the outputs of mutation induction is an indispensable tool not only in plant breeding research but also in fundamental genetic research activities related to gene discovery and gene function analyses.

Significant efforts are currently being made not only in the generation of genetic variations through induced mutations but also in the systematic characterization of the induced mutants for observed phenotypic and genomic changes and the cataloguing of the variations in searchable databases. Many of these databases are available to interested parties.

Climate change may well lead to significant losses of genetic diversity within species critical for food and agriculture. Roughly 20–30% of species assessed are likely to be at high risk of extinction, if global mean temperature exceeds 2–3°C above pre-industrial levels. These include crops' wild relatives, which are essential to increasing agricultural productivity, but also serve as the foundation for adaptation strategies required for adjusting to abiotic changes such as heat, drought and salinity as well as pests and diseases. Loss of genetic diversity would have important negative consequences locally as well as internationally, because key traits for climate change and variability adaptation may be lost forever. Mutation induction can help to meet this challenge.

Most national governments have also established germplasm collections that contain sizable amounts of characterized mutant stocks that are distributed to plant breeders and geneticists. The United States Department of Agriculture, Agricultural Research Service (USDA/ARS) runs several germplasm repositories (GRIN) that also include mutant genetic stocks under the National Plant Germplasm System (http://www.ars-grin.gov/npgs/holdings.html) and is considered to be one of the most comprehensive and best organized collections.[26]

In addition to these genetic resources with mostly single point mutations, another type of mutant genetic resource, radiation hybrids (RH), has been developed for genomic research. RHs are produced by exposing somatic cells to lethal doses of gamma radiation or X rays, in order to fragment the chromosomes. They are then rescued by introduction into host cells, which are subsequently fused with suitable recipient cells for the assessment of their expressions providing unique materials for the establishment of physical maps, a process known as radiation hybrid mapping. RH maps have been developed in a number of crops, such as barley, maize, wheat and cotton for gene discovery and detailed linkage analysis. This may soon lead to the identification and transfer of genes affecting useful agronomic, quality and stress tolerance traits.

[26] Information in the FAO/IAEA Database of Mutant Variety and Genetic Stock has been voluntarily contributed by national agricultural research institutes and breeders such as the Radiation Breeding Institute of Japan and Zhejiang University in China (an IAEA Collaborating Centre). For the IAEA mutant germplasm repository (MGR), please see http://mvgs.iaea.org .

I-3. Nuclear methodologies: enhancing efficiency through the application of biomolecular technologies

I-3.1. Novel molecular biology strategies for enhancing the efficiency of mutation induction techniques

A major bottleneck in the routine application of induced mutagenesis to both crop improvement and genomic research (through forward and reverse genetics) remains the drudgery of producing, handling and assaying the requisite large mutant populations. This is because mutant events usually occur in low frequencies and detection therefore requires the creation of large mutant populations. Molecular biology strategies, by permitting the querying of the genome, provide neutral tools that are independent of environmental or other extraneous factors for characterizing living organisms. One molecular biology strategy, reverse genetics—the use of modifications at the molecular level to predict phenotypes, holds great promise for reducing the number of putative mutants for expensive field trials or laboratory analysis, since plants without any alteration in the target gene could be effectively excluded from those tests.

Recent advances in genomics, especially publicly available genomics resources, have permitted the use of a high throughput platform such as 'Targeted Induced Local Lesions in Genomes (TILLING)' in the rapid evaluation of mutant stocks for specific genomic sequence alterations. TILLING is currently being used by many research groups in the identification of mutation events. In practice, the knowledge of the frequency of induced mutations in a population allows the calculation of the optimal population size, avoiding larger populations than necessary to be screened. Therefore, a pre-test of mutation frequency is helpful before starting whole population screening. Populations with too low a mutation frequency should be discarded.

In recognition of the utility of this method in high throughput mutation discovery, many laboratories have set up the TILLING platform and a number of laboratories also provide TILLING services for specific plants.

Another problem is the need to have the mutated segment in a homozygous state so that the mutation, usually recessive, could manifest as a phenotype. Another major difficulty is the inherent problem of chimeras, a problem that is exacerbated in vegetatively propagated plants. A number of in vitro techniques have been shown to circumvent or significantly mitigate these bottlenecks to induced mutations. These include cell suspension cultures including somatic embryogenesis; doubled haploid production and rapid in vitro multiplication.

I-3.2. Cell and tissue culture

Cellular and tissue biology strategies enhance efficiency of induced mutation in crops. Related to the problem of production and subsequent detection of mutation events in homozygous genomes are the confounding effects of chimeras, especially in vegetatively propagated crops. This problem is mitigated through several cycles of vegetative regeneration (both in vitro and in vivo) of the mutagenised vegetative propagule (i.e. plant material used for the purpose of plant propagation, e.g. any highly meristematic part such as root and stem ends or buds, but also cuttings, leaf sections, or any number of other plant parts that could be induced to regenerate whole plants in vitro).

This is also expensive in terms of time and resources and could be circumvented through the use of cell suspension cultures as starting materials for inducing mutations. Cell suspension cultures take advantage of the potential of each plant cell to regenerate into a whole plant, a phenomenon known as totipotency. In practice, this involves the production of cell lines from callus followed by the regeneration of plantlets through somatic embryogenesis. Typically, single cells and small cell aggregates are cultured; these proliferate and complete a growth cycle while suspended in a liquid medium. Since this technique was demonstrated in 1956 with *Phaseolus vulgaris*, reproducible protocols have been validated for other plant species [I-10]. This ability to culture individual plant cells, from which whole plantlets will arise, permits the treatment of individual cells with mutagens. The resulting plantlets are genetically similar leading to significant gains in time.

Where protocols for somatic embryogenesis, through cell lines or friable embryogenic calli, for instance, are not available, plantlets could also be regenerated but at relatively lowered levels of homozygosity and enhanced levels of chimeral sectors through in vitro nodal segments. While this is not optimal, it is still better than using stem cuttings or other tissues for crops that due to biological or genetic characteristics can only be vegetatively propagated and for which microspore cultures followed by chromosome doubling are impracticable. If this route is taken, due consideration must be given to planning strategies for efficient dissociation of chimeras. Where multi-cellular meristematic tissues have been used as starting materials for the induction of mutations, several cycles of regenerations, with M1V4 being the minimum, are required to dissociate chimeras in order to approximate the homohistont state.

I.3.3. Doubled haploid production

Another bottleneck to induced crop mutations relates to quality and the inherent recessive nature of mutations. This leads to the masking of the mutation events in the appearance of the mutants by the dominant allele at the same gene locus. In a heterozygous background therefore, phenotypic manifestations of mutations are practically impossible to detect in the early progenies necessitating several cycles of crossing the plant with itself in order to produce homozygous recessives that express the recessive phenotype.

Again, totipotency is exploited in the regeneration of doubled haploids (DHs), when the chromosome number of gametic cells, i.e. pollens or anthers and egg cells, is doubled prior to regeneration of a plant [I-6] to mitigate this problem. This process could be incorporated into induced mutagenesis by the treatment of these gametic cells prior to regeneration of the doubled haploids. With spontaneous and/or induced doubling of the haploid chromosomes, homozygous individuals are produced, availing the researcher of the most rapid route to attaining homozygosity without having to cross the plant with itself [I-13]. By facilitating the possibility of targeting either the haploid or doubled haploid cells for mutation treatment, a mutation is captured in a homozygous, pure line [I-13]. These mutants are homozygous for all loci including the mutated segments of the genome being targeted for modification and subsequent detection. For seed propagated crops, doubled haploid strategies provide the fastest method for achieving homozygosity, as compared to self-pollination. The savings in time and cost are significant as recessive mutations usually are not detectable till the first self-pollination generation or later generations. Rapid advances in cellular and tissue biology techniques have resulted in the availability of reproducible DH protocols for over 250 plant species [I-9] covering most plant genera. The Agency has, through its coordinated research activities, supported the development of easily applicable DH protocols for many crop species. The DH methodology has been successfully used to expedite the pace for generating true breeding mutants in crops such as barley, wheat, rice. Salt tolerant wheat was produced in China by combining mutagenesis with anther culture and at the Agency's laboratories, DH was also used to generate a semi-dwarf (and hence lodging resistant) rice mutant from a salt tolerant but uncultivated wild relative of rice [I-3].

I-3.4. Ion beam mutation

Ion beams have been widely used in the research on material surface modification since the 1970s. Their application for mutation induction was started with low energy ions in China in the late 1980s and with heavy ions in Japan in the early 1990s. While ion beam technology has been used for food crop improvement in China, it has been more extensively used for floriculture plants in Japan.

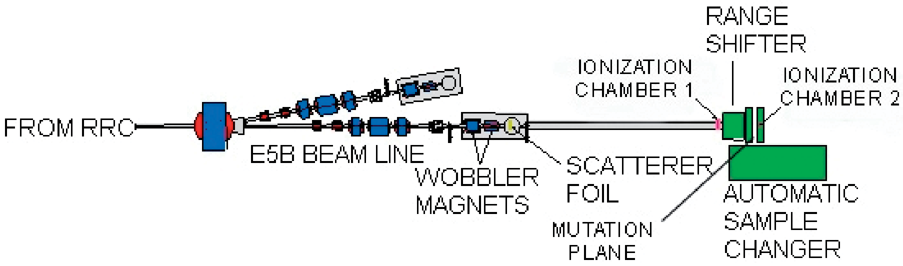

FIG. I-3. The schematic view of E5B beam line (RRC = RIKEN Ring Cyclotron). See Table I-1 for examples of heavy ions used in biological research [I-17].

Ion beams as a mutagen are different from other physical mutagens such as gamma or X rays in that they not only involve energy transfer (as gamma or X-rays), but also mass deposition and charge exchange; hence could result in complex DNA damage and changes that are not found when gamma or X-rays are used (high percentage of double strand breaks and subsequent chromosome aberrations). Ion beams are produced by particle accelerators, i.e. cyclotrons. Figure I-3 is a schematic view of the E5B beam line available in the RIKEN Accelerator Research Facility (RARF) Japan.

Typical ions used for irradiation on biological samples are neon-20, nitrogen-14, carbon-12, lithium-7, argon-40, iron-56 (Table I-1). They have different energy levels and linear energy transfer (LET), ionization densities which correlate to the complexity of DNA damage, and different ranges of penetration (Fig. I-4). It is possible to modulate the treatment of plant material with one species of ion at different LETs by passing the ions through a combination of absorbers – since changes in the LET of ion species occur as they pass through matter [I-17].

TABLE *I-1*. HEAVY IONS FOR BIOLOGICAL RESEARCH IN RIKEN ACCELERATOR RESEARCH FACILITY (RARF) [I-17].

Ion	Energy		Charge	Range in Water (mm)	LET (keV/μm)
	MeV/u	GeV			
^{12}C	135	1.62	6+	43	22.5
^{14}N	135	1.89	7+	34	26.3
^{20}Ne	135	2.70	10+	23	61.1
^{40}Ar	95	3.80	17+	8	280.0
^{56}Fe	90	5.04	24+	4	624.0

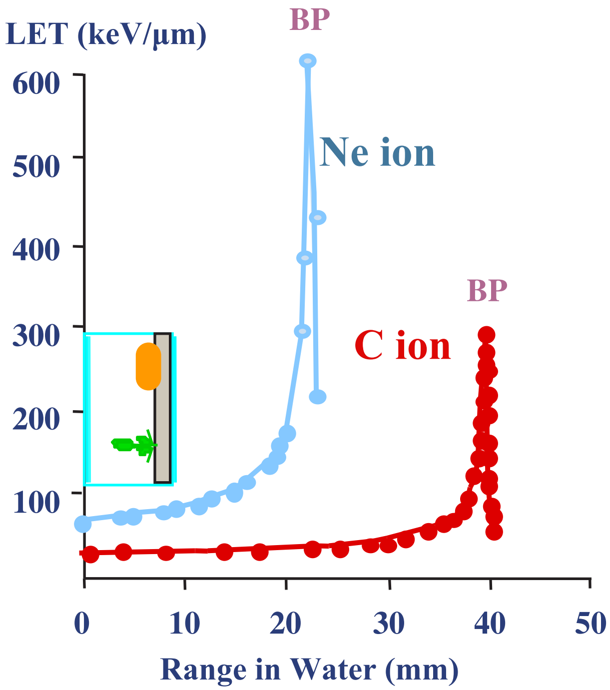

FIG. I-4. After a beam with sufficient energy penetrates a plantlet and/or plant tissue with rather low and uniform LET, the LET will then drastically increase towards the end of the track which is known as the Bragg peak (BP) [I-17].

Studies have shown that the biological effect of ion beam radiation is dependant on absorption doses and LET values but independent of ion species [I-17], which means that the treatment of carbon-12 would produce similar biological effect on rice seeds as neon-20 if the same dose (say 50 Gy) and same LET (say 30 keV/µm) is applied. DNA double strand breaks are believed to be the most important consequence of ion beam radiation. Very complex repair mechanisms have been unveiled but are prone to errors due to double strand breaks and lead to deletions, insertions, inversions and translocations. Studies on the mutant gene alleles induced by ion beam radiation showed that most mutations are deletions and that the size of DNA deletion is LET dependent.

Most complex DNA damage caused by the intricate set of effects of heavy ion beams (HIB) escapes the repair efforts and thus is described as more biologically effective and mutagenic than X-rays and gamma rays. A wider mutation spectrum and less collateral physiological damage (i.e. effect on plant survival and growth) is commonly reported for ion beam radiation as compared to other mutagens, which is considered an important advantage.

In China, 23 new rice and wheat mutant varieties have been bred using ion beam technology and released for large scale commercial production (more than one million ha per annum). The wheat variety 'Wanmai 54' displayed excellent resistance to head scab disease and rust disease and recorded the highest yield in the national new wheat variety yield trial (2003–2007), with yield increases over control variety of 7~10.6%. In Japan, ion beam technology has been used for generating mutants for a vast number of plant species by various researchers; for example, a consortium of more than 90 user groups was established to utilize the ion beam technology available in RARF (Japan). Six new flower varieties have been developed using this technology and marketed in Canada, Japan (Fig. I-5), USA, and the EU since 2002.

I-4. Future Perspectives

With the imminent threats posed by global climate change to crop production and the ever increasing and more sophisticated demands of agricultural products, crop improvement efforts have to be more powerful and precise in developing new crop varieties. Breeders therefore require tools that permit achieving subtle changes to the genetic make-up of otherwise superior crop varieties e.g. high yielding but lacking in specific quality traits, and yet leaving the genome largely intact in order not to disturb already stacked alleles of genes. The availability of genomics information in the public domain coupled with recent advances in molecular and cellular biology techniques have paved the way for transforming old mutation techniques into state of the art technology for both crop improvement and basic genomics research.

Development of novel and more efficient genomic tools have become routine and the pursuit of new physical mutagens continues. Some technologies are already in place and when integrated into mutation research, they will greatly increase the efficiency and application of mutation techniques in plant

FIG. I-5: First cultivation in 1998 of new chrysanthemum varieties using ion beams (courtesy of Dr. A. Takana, ISIMP2008/342).

research. For example, the next generation sequencing technologies, e.g. Roche 454 Genome Sequencer-FLX™ and Applied Biosystems SOLiD™ instruments, have the potential to reduce the cost of genome sequencing by several magnitudes, and simplify the process of mutation detection, the key point in mutation research and application programmes. In particular, they will enable the identification of mutant genes underlying important quantitative traits such as drought tolerance and yield, something that is still very difficult, if not impossible with traditional means.

Exposure of organisms to outer space conditions such as microgravity, vacuum, ultra-clean environment, cosmic rays, have allowed some countries, since the 1960s, to pursue programmes of "space breeding". While it is impractical to run commercial "space breeding" programmes, experiments in a simulated space environment are being conducted on earth using accelerator generated mixed high-energy particles that mimic secondary cosmic rays, including pion, meson, muon, positron, electron, photon and proton radiations. These may lead to the discovery of new physical mutagens that are more effective or have unique properties.

I-5. Conclusion

In conclusion, by facilitating the direct querying of target genes for changes, molecular biology techniques will significantly obviate the need for field trialling large populations. Additionally, robust; cheap and easy to use analytical methods will be 'hooked' up to these novel methods to enhance efficiency of the delivery processes. Cellular biology techniques will address the bottlenecks imposed by the need to rapidly generate large mutant populations of suitable genetic backgrounds (homozygous for the mutation events, and devoid of chimeras). New, space age technologies are being developed for mutation induction. The Agency is working with a network of experts with the objective of using a set of globally important food crops to validate identified relevant novel techniques and build these into modular pipelines to serve as technology packages for induced crop mutations. Thus, mutation assisted plant breeding will play a crucial role in the generation of 'designer crop varieties' to address the uncertainties of global climate variability and change, and the challenges of global food insecurity.

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Annex II

QUALITY ASSURANCE IN RADIATION DOSIMETRY: ACHIEVEMENTS AND TRENDS

II-1. Introduction

Dosimetry is the science of measuring radiation dosage. The absorbed dose of radiation is measured in a unit called ‘gray’ (Gy). Radiation dosage measurements and ensuring they are as accurate as possible are important if the benefits of the application of nuclear technology in health care are to be harnessed. Radioactive processes and radiation are utilized in many health related technologies, and the requirement for quality assurance (QA) and accuracy in dosimetry depends upon the specific needs of the particular applications.

In the case of delivering radiation to a patient as part of a treatment regime, accuracy is vital. The goal of a radiotherapeutic procedure is to deliver the dose required to eradicate a tumour while at the same time minimizing the radiation exposure to healthy tissue. Delivering too much radiation can result in serious complications that could harm the patient’s quality of life. On the other hand, delivering too little radiation to malignant tissue can ultimately result in the death of the patient as a consequence of the disease.

Dosimetry is also an important component in diagnostic medicine. In this case, the primary driver for accuracy is the need to balance the quality of an image with the amount of radiation exposure. By preventing unnecessary repetitions of imaging procedures, the cumulative dose to the patient is minimized, while still providing the information necessary to diagnose and monitor disease.

The use of radiation in hospitals, industry, laboratories and nuclear power plants also necessitates consideration of the potential radiation exposure to workers in the course of carrying out their duties. The level of accuracy required in dosimetry for the measurement of occupational dose is lower than that needed for patient dosimetry; however, traceability of measurements at a defined level of uncertainty is still important. Dosimetry is an essential component of all radiation safety and protection programmes designed to monitor and achieve the safe use of radiation.

There are industrial applications of nuclear technology that require radiation to be delivered at high doses. Some irradiated products may be used directly by consumers, as in the examples of irradiated food or sterilized medical products. Optimisation of irradiation delivery is important as the health and safety of individuals are at risk if the dose delivered to the product is inadequate to achieve the proper effect. Alternatively, if the dose is too high, resources will be wasted resulting in economic consequences. Hence the level of accuracy required in industrial processing dosimetry applications is determined by the economics of the radiation process and the processor's need to ensure that their product meets health and safety standards.

Requirements for safe and optimal use of radiation vary depending on the dosimetric accuracy required. Developing and implementing an appropriate QA programme will ensure fulfilment of these requirements. The main components of such QA programmes include traceability of radiation measurements through accurate calibration of instrumentation, training of staff, dosimetry audits and the establishment of quality control and radiation safety procedures.

Recent achievements and trends relating to dosimetry and QA of measurement standards, radiotherapy, diagnostic radiology, internal dosimetry, and radiation protection are described in the following sections.

II-2. Measurement standards

Reliable measurements are fundamental in dosimetry, and strategies have been developed to provide confidence using the traceability principle. The idea of traceability is that the result of a measurement, no matter where it is made, can be related to a national or international measurement standard, and this relationship is documented. The Bureau International des Poids et

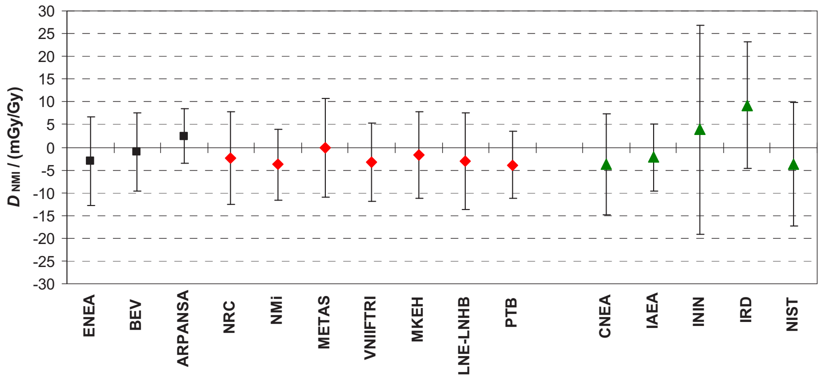

FIG. II-1. This figure, adapted from Ref. [II-2], shows an example of an international dosimetry comparison. It depicts the degree of equivalence between national dosimetry standards (x axis) with respect to the BIPM reference value y axis). The degree of equivalence to the Agency reference dosimetry system is also given.

Mesures (BIMP) ensures worldwide unification of physical measurements in radiation dosimetry [II-1] with the active participation of national dosimetry laboratories[27] which have their own measurement standards. Reference standards are maintained permanently at the BIPM and are used as a benchmark for comparison of national dosimetry standards [II-2]. This benchmarking has allowed some national laboratories to improve their standards as well as prompted the dosimetry community to strive for improved accuracy. For example, development of primary standards for the absorbed dose to water for high-energy photon and electron beams [II-3 and II-4] in the past few years, and improvements in radiation dosimetry concepts have reduced the uncertainty in the dosimetry of radiotherapy beams. The concept of dosimetry comparisons is now widely accepted and recognized as an important element of QA programmes and also recommended in recent ISO and IEC guides [II-5] and ICRU Report 76 [II-6]. It can also be used as a tool to demonstrate the calibrations and measurement capabilities of national calibration laboratories and to seek accreditation.

II-3. Dosimetry in radiotherapy

Radiotherapy involves delivering large amounts of radiation to specific targets within the human body. A high degree of accuracy, reliability and reproducibility is necessary for safe and effective radiation treatment of cancer patients. This ensures confidence in both the dose delivered to the tumour, as well as to the nearby healthy organs and tissues, thereby maximizing tumour control and minimizing adverse radiation effects. QA programmes have increasingly important roles as radiotherapy technology becomes more complex. Equipment designs are evolving and more complex treatment techniques are being implemented. For example, conformal radiotherapy is now widely available; this modality enables higher doses to be delivered to the tumour and therefore should increase the cure rates. Intensity modulated radiotherapy (IMRT) is a similar technique, which is built upon conformal radiotherapy but takes the concept further by using a multileaf collimator (MLC) to deliver a series of smaller concisely targeted fields of radiation. For the application of these small fields dosimetry errors can be considerably larger than with conventional beams mostly due to two reasons; (i) the reference

[27] A network of Secondary Standards Dosimetry Laboratories, known as the IAEA/WHO Network of Secondary Standards Dosimetry Laboratories (SSDLs) was established jointly with WHO in 1976. At present this network includes 80 laboratories in 67 Member States.

conditions recommended by existing dosimetry codes of practice cannot be established in more complex machines and (ii) absorbed dose to water measurements in composite fields are not standardized and reference conditions are not yet defined. To address these problems, an international working group has been established by the Agency in cooperation with the American Association of Physicists in Medicine (AAPM) to develop recommendations for reference dosimetry of small and non-standard fields. [28]

New technologies, such as IMRT, intensity modulated arc therapies (IMAT), volumetric intensity modulated arc therapy (VMAT), together with other newer radiation delivery platforms, such as TomoTherapy and CyberKnife, all require complex QA and verification methods for dosimetry. In light of these technologies, new QA devices such as two dimensional (2-D) array detectors, 3-D based detectors, radiochromic film, and thermoluminescent dosimeter (TLD) sheets, are becoming available and the dosimetry verification techniques in radiotherapy are evolving accordingly. Gel dosimetry is also used to verify complex 3-D dose distributions; however, it is not yet widely used. In the past few years a new technology has been emerging in some countries with hospital based facilities employing proton and light ion beams for radiotherapy. The advantage of using these radiations is that they allow for greater control of radiation dose distribution, thus enabling higher doses to tumours and lower doses to healthy tissue. Similarly to photon and electron beam treatment, planning of this high precision conformal therapy requires accurate dosimetry and beam calibration in order to ensure exact delivery of the prescribed dose. A major obstacle to establishing such dosimetry stems from the fact that these are different types of radiation, and primary dosimetry standards for proton and light ion beams do not currently exist. Current practice utilizes ionization chambers with cobalt-60 calibration coefficients, recognized as the most practical and reliable reference instrument for dosimetry of proton and light ion beams. The recent report from the International Commission on Radiation Units and Measurements (ICRU) on proton therapy [II-7] has recommended the use of IAEA Technical Reports Series No. 398 [II-4] in practical dosimetry. The ICRU report has also adopted the most recent developments in the field of ionization chamber dosimetry for these beams.

[28] This included providing training opportunities for about 100 medical physicists, from across the world, educational programmes on the use of these technologies through IAEA workshops and courses organized in collaboration with the Abdus Salam International Centre for Theoretical Physics, the AAPM and the European Federation of Organizations for Medical Physics.

One notable method for verifying the dose delivered to patients is by using direct measurements taken while patients are being treated, i.e. in vivo dosimetry (see patient setup in Fig. II-2). In vivo dosimetry provides insight into the accuracy and precision of the treatment delivery, detection of systematic errors and helps in the prevention of radiation accidents. Although such measurements may not prevent a single dose misadministration, they will minimize the possibility of escalating problems across many treatments or patients. Point detectors (1-D) used for in vivo dosimetry utilize various solid state detectors (semiconductor diodes, MOSFET, TLD, OSL) and are generally considered useful for patients treated with uniform intensity beams, in particular in radiotherapy centres where on-line electronic verification of treatment set-up parameters (through records and verify systems[29]) are not available. However, some issues are arising because point detectors are not suitable in non-uniform radiation fields with rapid dose gradients, such as those relevant to IMRT. To verify the IMRT dose delivery, 2 D in vivo dosimetry methods are being developed based on the electronic portal imaging device (EPID) attachments for treatment machines. EPID dosimetry is used in advanced academic radiotherapy centres but at this time it is not commercially available. The newest methodology for 3D in vivo dosimetry is under development, based on the reconstruction of the dose distribution from EPID measurements and patient images taken during the treatment using on-board imaging devices.

To ensure quality care, it is generally recognized that there is a continual need for national and international comparisons and audit programmes for radiotherapy dosimetry such as those conducted by the IAEA/WHO [II-8], Radiological Physics Centre (RPC) in USA [II-9] and other national and international organizations [II-10]. TLD auditing programmes have significantly improved the compliance rate among participating radiotherapy centres with regard to dosimetric accuracy. Other current dosimetry auditing programmes used for the verification of treatment planning and dose delivery, including those developed by the Agency [II-11] and RPC [II-12], are based on solid (anthropomorphic and semi-anthropomorphic) phantoms because of the multidimensional dosimetric aspects necessary in these techniques. They are used for a variety of dosimetric situations, including dose measurements in advanced conformal radiotherapy techniques and IMRT. The experience

[29] Records and Verify (R&V) systems are interfaced with linear accelerators and are used to verify treatment parameters.

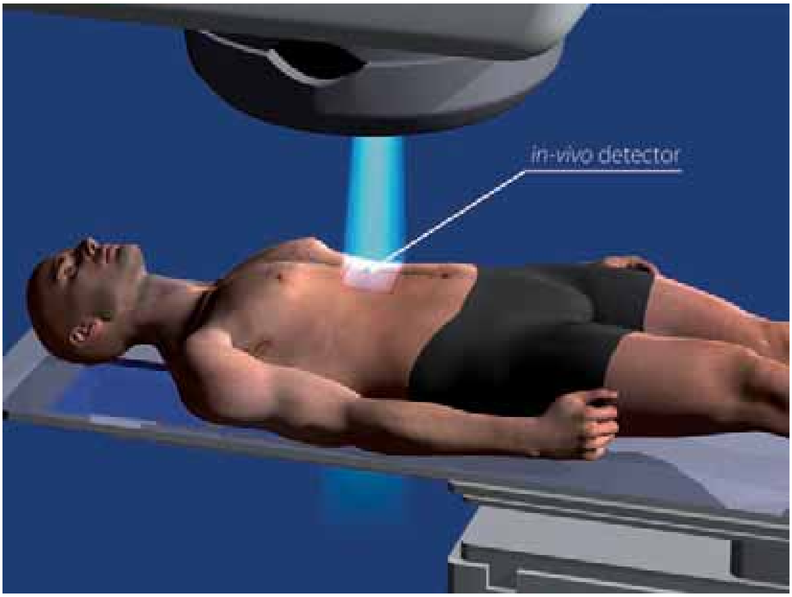

FIG II-2. Set-up for in vivo dosimetry during cancer patient treatment with a radiation beam. The dose delivered to the tumour during treatment is derived from measurements with a radiation detector placed on a patient's skin during irradiation and compared to the planned dose.

gained in external audits for complex techniques, such as IMRT, has shown that careful attention must still be given to basic aspects of dosimetry.

II-4. Dosimetry in X ray diagnostic radiology

Radiology is an area of medicine which has witnessed significant technologic developments in recent years including the advancement of new imaging techniques such as digital radiology, interventional radiology and computed tomography (CT) in order to improve and enhance patient care. However, while these developments have undoubtedly conferred benefits to a large number of patients, they have also raised concerns for the quality and safety of practices because the use of radiation for medical diagnostic examinations is a significant source of human-made radiation exposure. Therefore, the impact of these technical developments has to be quantified through measurement with the use of appropriate and internationally recognized dosimetry protocols and standards.

Diagnostic dosimetry measurements vary from the use of simple dose indicators used to provide information on the general magnitude of the radiation dose delivered to a patient, to more detailed and complex estimations of the dose, including estimations of the dose to particular organs for typical patient models. Dose indicators play a pivotal role in the control of patient dose as they allow trends to be identified and prompt corrective action on a local level through the use of optimization processes. Accurate determination of organ based radiation dosimetry provides useful information regarding biologically relevant radiation tissue damage and aids in the statistical estimation of risks to the population. Population risks are particularly important for low to medium dose usage of radiation as this comprises the majority of examinations performed in diagnostic radiology. Research is therefore being actively conducted on the development of methodologies for more accurate patient specific models and organ specific dosimetry. This work is most active and notable in computed tomography and interventional radiology, where considerable patient exposure can occur.

Standardization of dosimetry and calibration protocols is clearly central to the effectiveness of dosimetric measurement necessary in diagnostic radiology. This has recently been addressed in publications by the ICRU (Report 74) [II-13] and by an IAEA Code of Practice (Technical Reports Series No. 457) [II-14]. These complementary documents set out standards for the measurement of the diverse range of dosimetric quantities necessary to tackle the challenges of the rapidly changing and expanding environment of diagnostic radiology. Many laboratories have commenced development of a standardized set of reference beam qualities and some countries have started providing calibration services to hospitals.

Dosimetry audits and comparison are not fully developed in this field. More work is needed by the international community to set-up external dosimetry audits and comparisons to reach the same level as in radiotherapy dosimetry.

II-5. Internal dosimetry

In nuclear medicine imaging, patients are injected with radiopharmaceuticals and then imaged with radiation detecting cameras. Distribution of isotopes in the body presents the need for internal dosimetry, which currently is most often based on standard reference tables published in medical internal radiation dose (MIRD) pamphlets. These tables give the average absorbed dose to the main human organs for any specified amount of injected radioactivity. The tables were calculated in computationally intensive simulations for a reference man (with an average weight, height and radioactivity distribution). The tables also provide a rough estimate of the dose distribution for all commonly used radiopharmaceuticals in nuclear medicine. This method for calculating radiation dose can be used as an estimate of the resulting organ doses for most diagnostic procedures.

The impetus for more accurate and patient-specific dosimetry comes mainly from an increased availability and use of therapeutic radiopharmaceuticals [II-15]. Such treatments deliver high doses of radiation to specific targets, with the intent of providing a curative or palliative effect however the resulting radiation dose absorbed by both the target and healthy organs is several orders of magnitude higher than what is received from a diagnostic scan. The demand for more accurate and possibly patient specific internal dosimetry has grown accordingly. This demand is partially being met by developments in the methodology by which the patient specific dose is calculated, and also by computer-based tools available for the implementation of the improved methods. Dedicated software packages exist to aid in patient-specific dosimetry calculations.

The tools for calculating absorbed doses have become more sophisticated, covering the whole spectrum from estimating the whole-body dose to evaluating the specific radiation energy deposited in single cells. These important tools are however partially based upon assumptions and depend on user calculation and input of the true radioactivity distribution for individual patients in order to perform accurate dose calculations. Accurate quantification of the radioactivity distribution within the patient is thus essential for internal dosimetry (see Fig. II-3). Methods to track the radioactivity distribution in patients over time can include measurement with an external probe; measuring the amount of radioactivity in blood samples; and also includes efforts to quantitate the images from gamma camera scans [II-17]. All these methods are currently being refined with the involvement of the Agency.

As the methods and tools for more precise internal dosimetry are developed, it is important that medical physicists and other health professionals are continuously updated and trained so that the shortage of professionals with adequate skills in internal dosimetry does not lead to an unnecessary delay in the clinical use of novel and promising therapeutic radiopharmaceuticals.

Workers in different nuclear applications are potentially occupationally exposed due to intakes of radionuclides while working with unsealed sources of radiation. From the source activity measured the intake of radionuclide is assessed and the committed effective dose is calculated. New detection methods, metabolic and dosimetric models are currently under development to better represent the transfer of radionuclides and exposure process in the human body.

II-6. Dosimetry in radiation protection

Radiation protection is an essential infrastructure element in the use of radiation-based technologies in medicine, industry, agriculture, space exploitation, education and research. Radiation protection measurements require a dependable level of accuracy as they can have serious implications and can significantly influence practices. This is particularly true for applications related to health and safety of individuals and the public. Radiation fields can be very complex, depending on the practice and type of radiation involved. The wide range of ionizing radiation applications requires a wide range of instruments for characterizing various radiations and their intensities.

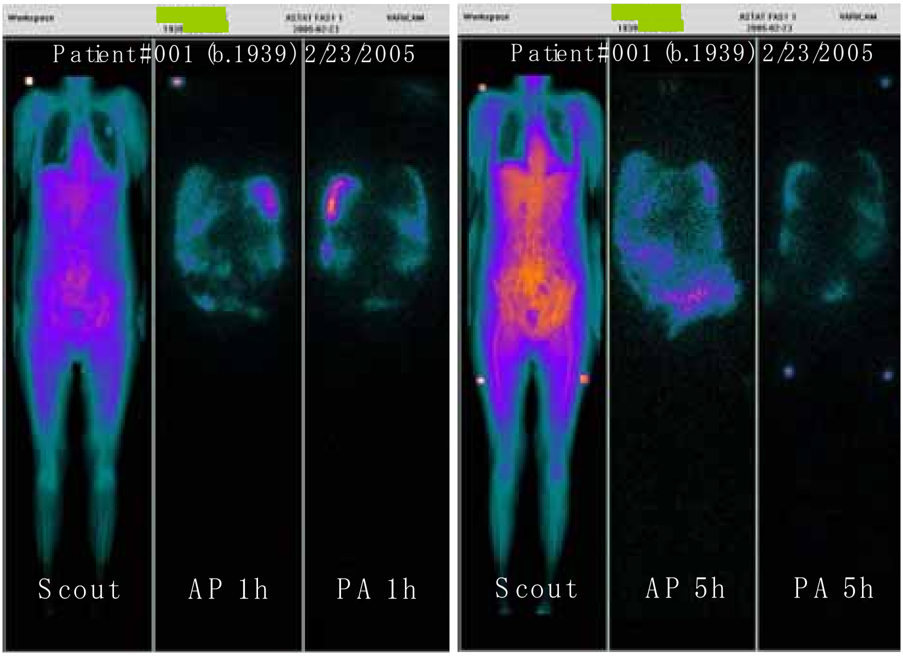

FIG. II-3. X ray and gamma camera images of a patient with ovarian cancer being experimentally treated with the alpha particle emitter astatine-211 labelled to a molecule that targets the cancer cells. In addition to alpha particles, astatine-211 also emits photons that can be detected by a gamma camera. The three panels on the left show the distribution 1 hour after the radiopharmaceutical was infused into the peritoneal cavity. The X ray image on the far left was acquired simultaneously with the gamma camera images of the front (AP) and the back (PA) of the patient. The three panels on the right show the distribution 5 hours after the infusion. When combined and analysed, these images provide information on the radiation absorbed dose to tumour and critical healthy tissue. The information is used to predict the therapeutic and toxic effects of this treatment (courtesy of University of Gothenburg, Sweden).

External dosimetry is necessary for workplaces where there is medical or industrial use of ionizing radiation. This primarily involves using detectors and dosimeters for measurement of photons, neutrons and beta radiation for area monitoring and personal dosimetry. More traditional personal film dosimetry systems are being gradually replaced by solid state detectors thermoluminescence (TL), radiophotoluminescence dosimeters (RPL,) and optically stimulated luminescence (OSL) and electronic dosimeters. Rapid development of medical applications of radiation, mainly interventional radiology, requires new approaches in monitoring medical staff. Comparisons of dosimetry systems for monitoring of occupational doses have been organized by the European Union and the Agency. These types of exercises are widely accepted as an efficient tool for harmonization of dosimetry approaches and quality assurance of services provided to end users. Radiation protection also faces challenges in addressing problems associated with radiation produced by high energy accelerators, nuclear power installations, and radiation received on aircraft or during space missions, and requires the use of a broad range of techniques for measurement of photons, electrons, neutrons, protons and other charged particles as well as techniques in computational dosimetry. Behaviour of many dosimetry systems in such radiations is still not very well known. Assurance of the quality of measurements is achieved through joint benchmark exercises organized in facilities that can provide these types of radiations. Complex workplace radiation fields have been established at the European Organization for Nuclear Research (CERN) [II-16] and other high energy accelerator facilities, in nuclear installations, neutron calibration facilities and also in some radiotherapy facilities worldwide. Extensive research in this area is still required.

Another concern in radiation protection is environmental dosimetry. Environmental dosimetry is a field which aims to describe the distribution of natural and artificial radiation sources in the environment and assess the resultant doses to the general public and other species. It involves various active (ionization chambers, proportional and Geiger–Mueller counters, and spectrometers) and passive (TLD, OSL) dosimetry techniques used to assess short time and long time variations of radiation levels. Environmental dosimetry systems are linked to national networks thus providing continuous monitoring and early warning of nuclear accidents with local or transboundary implications. While the environmental dosimeters are calibrated at the laboratory, once used in the field they may lose traceability due to differences in radiation fields encountered during calibration and in the environment. Field comparisons play an important role during quality assurance of environmental measurements. The natural environmental radiation stations and underground testing laboratories, developed in the frame of the EU research programme, have been successfully used for testing various dosimetry and national network systems.

II-7. Conclusion

Technologies which utilize radiation have shown enormous potential benefits for society. These benefits are best realized when proper knowledge of radiation dosimetry is incorporated into the science and application of the different technologies. While working modalities differ in the fields relevant to radiation dosimetry, efforts are continually being made to improve their accuracy. Strategies for measurements are applied worldwide to create common international standards and comparison platforms, which play an important role in QA programmes.

Radiotherapy is an example of an active field which relies heavily on these QA programmes to ensure that patients are receiving the most effective and safe treatments for their cancers. Advancements are being made in X ray diagnostic radiology but dosimetry audits and comparison procedures have yet to be implemented routinely. In nuclear medicine, pharmaceutical effects determine distributions of radioisotopes, and thus dose, within a patient. Work is currently being done to provide better patient specific, and organ specific dosimetry, which in turn, will aid in drug development and in the provision of better patient management. Non-medical and industrial exposures to radiation are also of great interest, and require accurate measurement tools and methodologies to monitor work places and public environments. As technology continues to grow, so do the efforts to assure safety, quality, and accuracy, in radiation related fields. Progress is being made through development of appropriate dosimetry, utilizing QA programmes, audits, new tools, and new ideas.

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Annex III

ISOTOPES FOR MANAGEMENT OF TRANSBOUNDARY RIVERS AND AQUIFERS

III.1. Introduction

Management of transboundary fresh water resources (also known as trans-national, international, or internationally shared water resources) is of increasing concern across the world. Transboundary water resources include visible surface water bodies, such as lakes and rivers that cross borders, and groundwater systems (or aquifers). Globally, over 260 transboundary river basins have been identified. These basins cover 45% of the land surface of the earth, affect ~40% of the world's population, and account for ~60% of the global fresh water supply [III-1]. Aquifers, including transboundary aquifers, account for the rest of freshwater supply. Some of the large transboundary aquifers include the Nubian and northwest Sahara aquifers in northern Africa and the Guarani aquifer in Latin America. However, in many areas no inventory of transboundary aquifers exists. The widespread occurrence of these systems is exemplified by a recent United Nations survey that identified 89 transboundary aquifers in Europe [III-2].

Although management of transboundary rivers and lakes has been an issue for many years, transboundary groundwater issues have largely been overlooked. This is partly because surface water and groundwater historically have been regulated as separate resources. However, the situation is starting to change. For example, a recent Agency co-sponsored conference, 'Groundwater and Climate in Africa' that was held in Kampala, Uganda, in June 2008, clearly demonstrated that predicted climate change scenarios will lead to an increased reliance on groundwater resources in Africa. Africa is already struggling with over exploitation of groundwater in some locations and some of the largest transboundary aquifers are essentially non-renewable [III-3] which increases the potential severity of climate change effects.

Cooperation for the sustainable management of transboundary aquifers is difficult to achieve in the absence of information regarding the links between surface water and groundwater, as well as groundwater recharge, residence times, and hydrological flow paths. Most conflicts over water between countries have generally been addressed by non-violent means. However, the lack of sufficient technical information regarding water resources increases the chances of misunderstanding and confrontational situations, especially under scenarios of decreased water availability and/or food scarcity (see the discussion in Ref. [III-4] and references therein).

Much can be gained through the application of traditional hydrological characterization such as measurement of water levels, river discharge measurements, etc. Despite the high value of such information, ambiguities about how these systems function and/or unacceptably large uncertainties about a particular water system all too often occur. This is why the application of isotope techniques (i.e. isotope hydrology) as part of the characterization process, can be an extremely important complement to traditional methods. Isotope hydrology can provide key information to build and test conceptual models of transboundary systems, and can also be extremely valuable for testing or parameterizing numerical models of hydrological flow systems.

III-2. Mapping transboundary water bodies and their characteristics

The first step in addressing key transboundary problems is to identify and map transboundary water bodies [III-2]. One important ongoing hydrological mapping effort is the World Hydrogeological Mapping and Assessment Programme known as WHYMAP (http://www.whymap.org/). An important product of WHYMAP relative to this transboundary discussion is a global scale map of major transboundary aquifers (Fig. III-1). This map shows the frequency of transboundary groundwater across the world. This kind of global scale mapping is typically too coarse for actual transboundary management purposes, but it does have an important role in raising awareness and educating policy makers and the general public about the fact that groundwater does not follow national borders. Another effort to make aquifer characterization data and maps (including transboundary related data) available to water resource managers is through the UNESCO initiated International Groundwater Resources Assessment Centre in the Netherlands (IGRAC, http://IGRAC). IGRAC is compiling detailed groundwater information from studies across the globe. The goal is to make key data and maps available to the public and at scales meaningful to water managers and stakeholders.

With regard to maps of isotopes and isotope data in general, the Agency has recently expanded its Water Isotope System for Data Analysis, Visualization, and Electronic Retrieval (WISER) worldwide web application (accessible through http://www.iaea.org/water/). WISER is a GIS based information system which makes a large amount of isotope hydrology data available for addressing local and regional scale transboundary water issues (as well as other water resource problems). The mapping application in WISER includes high quality cartographic representation, processing of topographic and thematic data, interactive manipulation and visualization of data. Various query, exploration and analysis tools are included to lead the user towards

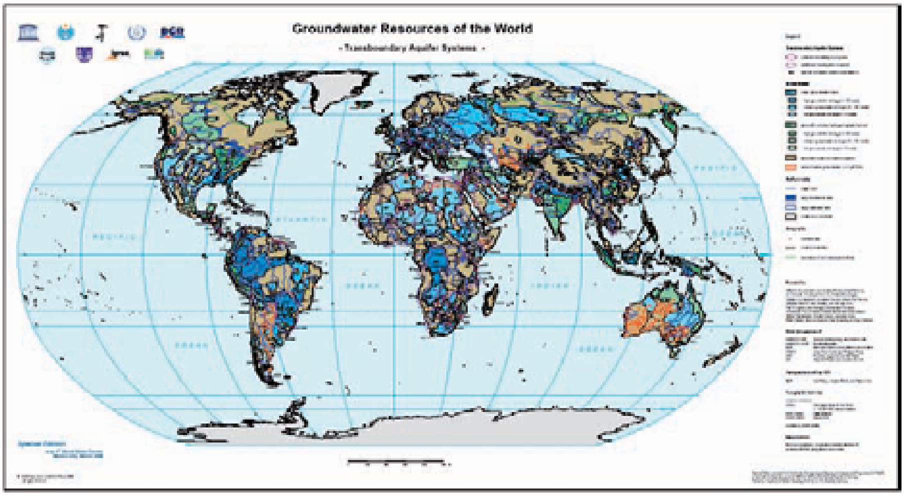

FIG. III-1. Transboundary aquifers of the world from the WHYMAP programme. While the term 'transboundary' often refers to two or more countries, it may also refer to internal boundaries within a country such as between states, provinces, or districts.

customised results. WISER contains unique isotope databases and spatial products that will increasingly play an important role for addressing transboundary water issues in the future (additional details are provided in references [III-5, III-6]). During roundtable discussions at the 2007 International Isotope Hydrology Symposium in Vienna, participants clearly indicated that the Agency's efforts involving WISER are very relevant. For example, the Global Network of Isotopes in Precipitation (GNIP) and the Global Network of Isotopes in Rivers (GNIR) databases within WISER were cited as examples of critical resources for isotope data at local, regional, and global scales. Because new data are continually added to the WISER system, its usefulness in understanding spatial relationships between isotopes and hydrological systems and temporal impacts from such factors as land use and climate change make WISER highly relevant to transboundary problems as well as other water resources issues [III-6]. An example of an isotope map for the Guarani aquifer in South America is shown below (Fig. III-2) and additional discussion of this map is provided later in this annex.

III-3. Developing conceptual models of transboundary systems

The simple conceptual models of transboundary water systems shown in Fig. III-3 below illustrate some of the basic characteristics that need to be understood for a given transboundary location. It is clear from the figure that simple questions such as where does the water come from, and where is it

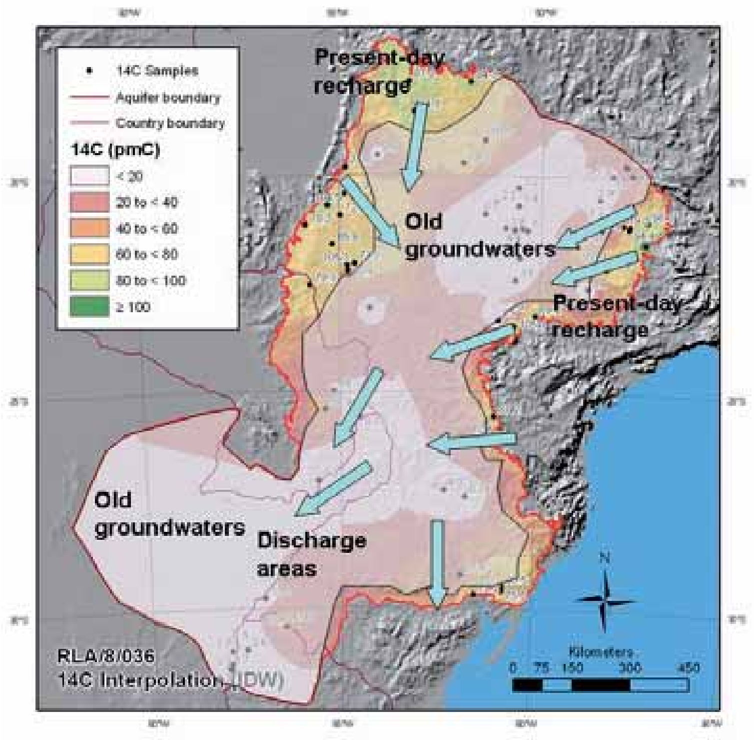

FIG. III-2. Carbon-14 distribution (per cent modern carbon, pmC) in the Guarani aquifer system in South America. Light coloured areas (low values of carbon-14) indicate parts of the aquifer with old groundwater (> 10 000 years). The arrows indicated inferred directions of groundwater movement, with aquifer recharge in the north and discharge in the south.

going, need to be answered if transboundary resources are to be used in a sustainable and cooperative way. However, in many transboundary cases around the world, it is currently not clear which of these simple models applies to a given hydrological system. In addition, in cases where the basic conceptual model is known, important details about the rates of movement, locations of recharge, or sources of contaminants may not be known. As illustrated in the examples below, future uses of isotope methods will contribute significantly to the development of conceptual models of transboundary water systems and help refine the quantitative aspects of such systems which are necessary for sustainable management. Such approaches are now being used to address transboundary water problems through various international collaborations. Two prominent examples are the Agency and UNDP/Global Environmental Facility collaborations on the Nubian and Nile systems in Africa (see Ref.

[III-3] for a review of these two transboundary systems). New collaborative efforts similar to these will certainly be utilized as an effective way to deal with transboundary problems in the years to come.

The effective use of isotope methods to understand a large transboundary aquifer system is well demonstrated by recent work in the Guarani aquifer of South America (Fig. III-2). The Guarani is one of the world's largest aquifers (over 1.2 M km^2) covering parts of Argentina, Brazil, Paraguay and Uruguay [III-7]. It is an important water source for industry, agriculture, and domestic supplies, and a better understanding of the functioning of the aquifer is required for sustainable management. A conceptual model of the aquifer based largely on carbon-14 analyses is shown in Fig. III-2. The carbon-14 results

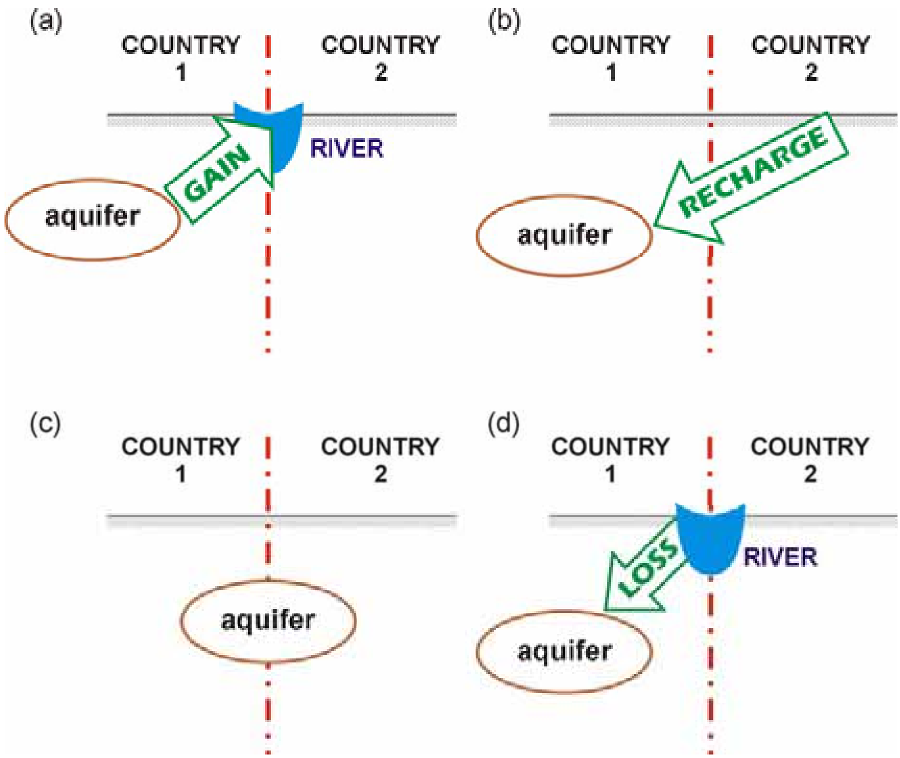

FIG. III-3. Conceptual models of groundwater and groundwater–surface water interactions in transboundary water bodies (modified from [III-4] and references therein). The dashed, red vertical line denotes the delineations between countries. Model A shows an aquifer in one country that discharges into a river on the boundary between two countries. Model B shows an aquifer in one country with a recharge zone in another country. Model C shows a groundwater aquifer that extends across a political boundary. Model D shows a shared border river that recharges an aquifer in only one of the countries.

revealed that much of the aquifer contains old groundwater, thus the system is vulnerable to groundwater mining. The presence of old water was also noted in Ref. [III-7] using chlorine-36 and uranium isotopes. Some present day recharge also occurs, so the aquifer management strategy must account for both of these situations. It is also important to note that some countries contain the present day recharge areas, while others contain the discharge areas. Thus, the information shown here can significantly aid the four Guarani aquifer countries in their efforts to build a cooperative transboundary management strategy.

Radon-222 is another isotope technique that is expected to see increasing use in the near future to address transboundary and other hydrological problems. Radon-222 has been used for hydrological studies for many years [III-8] and its particular usefulness lies with the fact that most groundwaters are enriched with radon-222, while activities in surface waters are typically very low. Thus, it can be used to map and quantify groundwater discharges into lakes and streams, and also into marine coastal zones [III-8–III-10]. For example, a groundwater discharge zone in a river typically has substantially higher radon-222 activities than nearby river reaches above or below the groundwater discharge zone. Knowing where groundwater discharge is occurring is an important conceptual and quantitative factor when addressing transboundary water problems as indicated by the conceptual models in Fig. III-3 (e.g. model A). However, the short half life of radon-222 (3.83 days) has hampered its broader use because of the need to conduct liquid scintillation analyses within a few days after sampling to avoid excessive decay. On the other hand, the availability of a relatively low cost, portable, yet high precision and accuracy radon-222 detector capable of analysing a wide range of radon-222 activities in water (Fig. III-4) should increase the use of radon-222 in hydrological studies. The detector can be used to analyse collected water samples [III-10] or make in situ measurements directly within a surface water body [III-9]. The instrument and associated water analysis attachments (Fig. III-4) will make it far easier for investigators to obtain radon-222 in groundwater and surface water with out the need for rapid transport and analysis and if desired without collection of samples at all. The in situ measurement capability makes it possible to obtain high resolution distribution information on the spatial variability of radon-222 in a surface water body and also to collect temporal data at a 30 minute or less time resolution.

As a transboundary application example, the Agency supported the International Commission for the Protection of the Danube River (ICPDR) to help improve understanding of the basin surface water and groundwater system through the application of isotope techniques. In the summer of 2007, the ICPDR launched the second Joint Danube Survey (JDS-2) to collect information regarding water quality and ecological sustainability of the

FIG. III-4. Photo of the RAD-7 radon detector (small dark box with printer on top) and RAD AQUA system (blue cylinder) in operation on board the Joint Danube Survey ship Argus in 2007. River water is being pumped through the RAD AQUA where it releases radon gas that is then pumped into the RAD-7 for detection of radon-222.

Danube. The survey entailed collection and analysis of samples for a wide variety of water quality, hydrological, and other parameters. The survey began in Regensburg, Germany, and finished 50 days later in the Black Sea. Samples were collected by ship at over 90 points along 2375 km of the river covering ten different countries. The radon-222 data were collected to identify potential locations with significant groundwater inputs and also to examine mixing between the Danube and its tributaries. The radon-222 profile along the Danube has some interesting features as shown in Fig. III-5. Overall, the values are low and the lowest values are effectively at the limit of detection as is typical for surface water. However, there are significant differences between some parts of the Danube and between the Danube and some of its tributaries. The overall trend is for higher radon concentrations in the upper Danube which suggests that this is the area where groundwater contributions to the river are the largest. Some of the tributaries (e.g. the Sava, Velika Morava and Siret) also have high radon-222, which suggests they have groundwater inputs

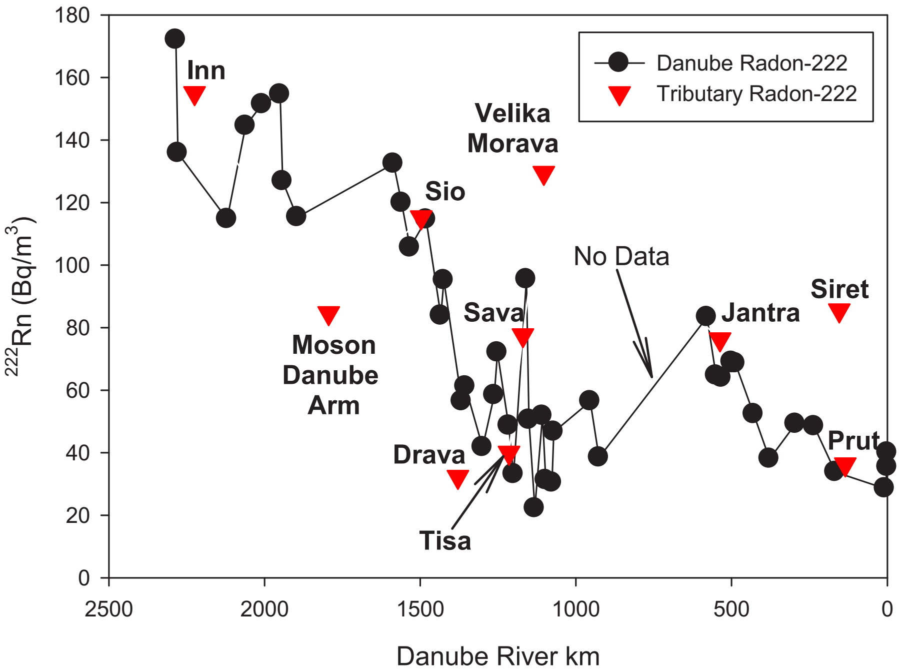

FIG. III-5. Radon-222 in the Danube Basin. Uncertainties are better than 30 Bq/m^3.

in the vicinity of the JDS2 sampling points. In terms of mixing, the Sava appears to have the largest impact on the Danube radon-222 values although values drop off quickly until the Velika Morava and then they decrease rapidly again. Although the Siret has relatively high radon-222, its impact on the Danube appears to be minor and is within the measurement error. This lack of impact is probably related to the low discharge of the Siret relative to the Danube.

III-4. Final Discussion and Conclusions

There are other important areas and approaches where the use of isotopes for solving transboundary water issues is expected to grow. One such example involves nitrate, one of the most common transboundary contaminants. Isotope analyses of nitrate are now used to identify contaminant sources and evaluate the extent of biodegradation which are key factors in the prevention and mitigation of nitrate contamination. For example, nitrate isotopes from a transboundary aquifer system in western part of Canada and the USA showed that much of the contamination was originally derived from manure with an increasing contribution from inorganic fertilizers [III-11].

The use of isotope hydrology will continue to grow because of the increasing need to properly assess and manage water resources. This is especially true for transboundary water systems where a sound, scientific understanding of the hydrology and geochemistry is essential for sustainable resource management, but also to further peace and cooperation between countries using shared water resources.

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Annex IV

ADVANCED CONSTRUCTION METHODS FOR NEW NUCLEAR POWER PLANTS

IV-1. Introduction

Relative to coal fired and natural gas fired power plants, nuclear power plants are more expensive to build but less expensive to run. This annex describes advanced construction methods to reduce nuclear power's construction costs, mainly by shortening the time needed to build a plant.

Each of the methods described below has been used in one or more of the projects listed in Table IV-1. None is unique to the nuclear industry, nor to any specific nuclear power plant design. Most are also used for other large construction projects such as fossil fuel power plants, large civil construction projects and shipbuilding.

IV-2. Open top installation

Constraints on installing major components inside the reactor and containment building can have a major impact on the construction schedule. In the past, the walls of the reactor and containment building were constructed with temporary openings to allow the entry of large equipment. In open top installation (Figs IV-1 and IV-2), the reactor and containment building is built with a temporary roof with an opening through which major pieces of equipment, such as the reactor vessel and steam generators, can be lowered into position using very heavy lift (VHL) cranes. Today's VHL cranes can lift equipment weighing more than 1000 tonnes, with very long reach. Once the equipment is placed inside, piping and electrical systems can be installed at the same time that construction of the reactor and containment building is being finished, including the replacement of the temporary roof by a permanent containment dome.

Open top installation has been used successfully with modularization (see next section) to shorten construction schedules. VHL cranes add additional costs, but these are more than compensated for by the shortened construction time. VHL cranes also add to planning requirements as it is vital to ensure that they are strategically placed to conduct multiple lifting activities including the installation of heavy equipment in other buildings of the plant or to provide lifting capabilities for two units being built concurrently next to each other.

TABLE IV-1: REACTORS BUILT RECENTLY USING ADVANCED CONSTRUCTION METHODS [IV-1–IV-5]

Reactor	Country	Construction period (months)*	Start of commercial operation	Type of reactor (approx. MW(e)) **
Kasiwazaki Kariwa-6	Japan	48	Nov. 1996	ABWR (1350)
Kasiwazaki Kariwa-7	Japan	48	Jul. 1997	ABWR (1350)
Lingao-1	China	60	May 2002	PWR (1000)
Lingao-2	China	62	Jan. 2003	PWR (1000)
Qinshan 3-1	China	54	Dec. 2002	PHWR (720)
Qinshan 3-2	China	58	Jul. 2003	PHWR (720)
Tarapur-3	India	75	Aug. 2006	PHWR (540)
Tarapur-4	India	66	Sep. 2005	PHWR (540)
Shin Kori-1	Republic of Korea	54 (planned)	Dec. 2010 (planned)	PWR (1000)
Olkiluoto-3	Finland	70 (planned)	Jun. 2012 (planned)	EPR (1600)
Kudankulam-1	India	84 (planned)	Mar. 2009 (planned)	PWR (917)

* The construction period is generally considered to be the time from the first major pour of concrete for the main plant building to the commercial operation date.

** ABWR=advanced boiling water reactor; EPR=European pressurized water reactor; PHWR= pressurized heavy water reactor; PWR= pressurized water reactor

During the construction of Qinshan 3-1 and 3-2 in China, a VHL crane was used to position about 70 pieces of equipment (Fig. IV-1), including steam generators which weighed 220 tonnes each (Fig. IV-2), the pressurizer (103 tonnes), the reactivity mechanisms deck (43 tonnes), feeder frames (40 tonnes each), fuelling machine bridges (16 tonnes each) and major heat exchangers. It took just two days to install each steam generator instead of the two weeks required for traditional horizontal access installation.

Figure IV-3 shows a VHL crane lifting the 200 tonne containment liner double rings into place at Olkiluoto-3 in Finland, and Fig IV-4 shows the containment dome at Kudankulam-1, in India, being lifted into position.

During the construction of Tarapur-3 and 4 in India, open top installation was used to position about 50 pieces of equipment, including the steam generators (Fig. IV-5), moderator heat exchangers, several other heat

FIG. IV-1. Very heavy lift crane at Qinshan, China.

exchangers, pressurizer, calandria (Fig. IV-6), primary circuit headers and fuelling machine. The lowering and positioning of each steam generator was completed in less than a day, much less than the installation time of more than one month required by other methods.

FIG. IV-2. Installing a steam generator at Qinshan 3-1 in China

FIG. IV-3. Lifting the containment liner double rings at Olkiluoto-3 in Finland.

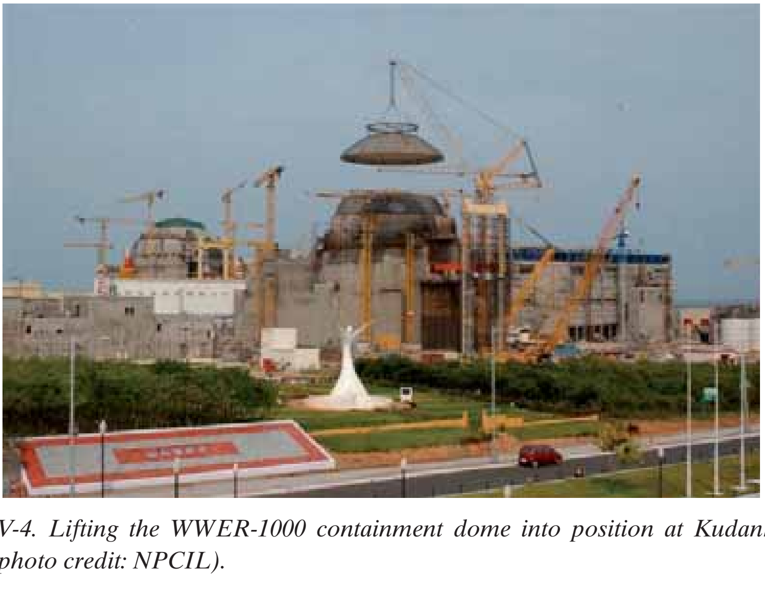

FIG. IV-4. Lifting the WWER-1000 containment dome into position at Kudankulam, India (photo credit: NPCIL).

FIG. IV-5. (a) and (b): Installing a steam generator at Tarapur-3, India.

IV-3. Modularization with pre-fabrication and pre-assembly

Prefabrication and pre-assembly of modules are construction techniques used in many industries, including nuclear power plants. A module is an assembly consisting of multiple components such as structural elements, piping,

FIG. IV-6. Lifting the calandria at Tarapur-3 in India.

valves, tubing, conduits, cable trays, reinforcing bar mats, instrument racks, electrical panels, supports, ducting, access platforms, ladders and stairs. Modules may be fabricated at a factory or at a workshop at the plant site, and multiple modules can be fabricated while the civil engineering work is progressing at the site in preparation for receiving the modules. This reduces site congestion, improves accessibility for personnel and materials, and can shorten the construction schedule. It can also significantly reduce on-site workforce requirements.

Modularization also facilitates mass production of modules in the event that several reactors are being built at the same time. Mass production reduces production times and labour requirements. Modularization makes it easier to ensure a controlled production environment, with associated improvements in quality and efficiency. It makes it possible to manufacture modules before the site itself is available, and, in the case of concrete, it facilitates the use of accelerated curing techniques.

The decision to apply a modular approach should be made in the conceptual design stage, and then it must be followed throughout the project, for detailed design, engineering, procurement, fabrication, and installation, through to the completion of commissioning. This allows equipment to be designed to conveniently fit into a module, and for modules to be sized to match the capacity of VHL cranes and transport routes to the site. A site accessible by sea can accept larger modules. For less accessible sites, sub-modules can be shipped to the site and then assembled into larger modules before installation. Modularization also affects testing procedures as many components can be initially tested at the fabrication facility to help eliminate potential faults before formal post-installation tests at the construction site.

Other impacts of modularization are: the need to complete the total plant design before fabricating modules; the need for factories or workshops to fabricate modules; earlier expenditures on engineering, materials and components for fabricating modules; the need for expensive heavy lift cranes; and the costs of transporting modules.

Modularization with prefabrication and pre-assembly has been used in combination with open top construction in recent construction projects for evolutionary water cooled reactors [IV-1]. At Kashiwazaki Kariwa-7 in Japan, the seven floors of the reactor building were divided into three modules and fabricated in a pre-assembly yard before the pieces were successively lifted into place by a VHL crane. The heaviest, most complicated module was the 'upper drywell super large scale module' which consisted of a γ shield wall, pipes, valves, cable trays, air ducts and their support structures and weighed 650 tonnes (Fig. IV-7).

FIG. IV-7. Installing the upper drywell super large scale module at Kashiwazaki Kariwa-7 in Japan.

At Lingao-4 in China, the containment dome was assembled on the ground at the site and installed as a single module weighing 143 tonnes with a diameter of 37 metres and height of 11 metres (Fig. IV-8). Previously, the dome would have been assembled by moving sections into position — a process that normally took about two months.

The Shin-Kori-1 and -2 projects in the Republic of Korea modularized the fabrication and installation of the containment liner plate. This forms the inner structure of the containment building for the Korean Optimized Power Reactor. Normally, the installation process would have fifteen stages, each involving the installation of one containment liner plate ring. At Shin-Kori-1 and -2, except for the first ring, all the other rings were modularized into two-ring sections and installed with one lift for each section (Fig. IV-9). The number of lifts is reduced, and the overall construction period is shortened. This method also simplifies connections with auxiliary buildings since connecting provisions, such as penetration sleeves for piping and electrical wire, are attached to the ring modules before installation.

As a final example of modularization, at Tarapur-3 in India, the prefabrication of piping was increased to 60–70%, compared with approximately 40% for previous plants in India. This reduced field welding by 30–40%.

FIG. IV-8. Lifting the dome module into place at Lingao-4 in China.

FIG. IV-9. Modularization of the containment liner plate assembly at Shin-Kori-1 in the Republic of Korea.

IV-4. Advanced welding techniques

Nuclear power plant construction involves numerous welds to connect both components of structures and components of pressurized systems. It also involves weld cladding, which refers to one metal being deposited onto the surface of another to improve its performance characteristics. Quality welding is both crucial and time consuming, and techniques to increase the rate at which weld metal can be deposited while maintaining high quality can reduce construction times. Recent advanced welding technologies that meet this objective include gas metal arc welding, gas tungsten arc welding and submerged arc welding.

In addition, automatic welding equipment that makes it easier to weld in narrow spaces can further decrease construction times. Automatic welding equipment has been used to weld titanium tubes to condenser tube sheets at Tarapur-3 in India and to weld piping at Kashiwazaki Kariwa-7 in Japan (Fig. IV-10).

IV-5. Steel plate reinforced concrete and slip-forming

Reinforced concrete is used in the foundations of nuclear power plants and in structures such as reactor containments, auxiliary buildings, turbine buildings and spent fuel storage areas. Conventionally reinforced concrete is fabricated in place using reinforcing bars ('rebar') with external forms to frame the structure prior to pouring the concrete. The time required to place the reinforcing bars and to construct and remove the forms into which the concrete is poured is considerable. It is a major part of the construction schedule.

FIG. IV-10. Automatic piping welding at Kashiwazaki Kariwa-7 in Japan.

Steel plate reinforced concrete is an alternative to conventionally reinforced concrete [IV-6] and can be used for most floors and walls. The concrete is placed between permanent steel plate forms with welds to tie the steel plates, rebar and tie-bars together. The forms can include any necessary penetrations and piping runs. Because of structural credit for the steel plate–concrete combination, the amount of rebar may be reduced, and because the steel plate structure can be self-supporting, reinforced concrete sections can be modularized and prefabricated off-site, followed by placement and welding on site.

Figure IV-11(a) shows standard reinforced concrete, and Fig. 11-IV(b) shows steel plate reinforced concrete.

Steel plate reinforced concrete has been used to significantly shorten construction schedules at plants recently constructed in Japan.

Construction schedules can also be shortened by slip-forming with modular floor design technology. Slip-forming is the continuous pouring of concrete at a very specific, calculated and monitored rate that is achieved by continuous hydraulic lifting and moving of a short section (preferably less than two metres) of formwork while inserting steelwork and pouring concrete through the top. Using slip-forming, vertical walls can be constructed at a rate of about 2 metres per day compared to a typical value of 1.2–1.5 metres per day without slip-forming. Slip-forming requires a heavy lift crane to lift the heavy steelwork that is inserted while the concrete is being poured.

Modular floor design and installation are used in conjunction with slip-forming for the walls. After the outer vertical walls of a building are installed by slip-forming, the modular floors can be installed through the open top of the building by means of a heavy lift crane. Modular floors consist of steel modules, which include rebar but no concrete, that are placed on supports embedded in the concrete walls during the slip-forming process. The modular floors, which are designed to be transported from the site assembly shop and installed by cranes, are welded to the supports embedded in the walls and then filled with concrete.

IV-6. Rebar placement for reinforced concrete

Rebar installation by individual placement of bars is quite time consuming. Large amounts of rebar are needed in the base mat, containment walls, containment dome, and structural walls of the reactor and turbine buildings. The use of prefabricated modular rebar assemblies for these areas can shorten construction schedules.

(a) Reinforced concrete.

(b) Steel plate reinforced concrete.

FIG. IV-11. Comparison of reinforced concrete structures.

Automation is another way to speed the installation of rebar. There are several techniques. Figure IV-12 shows an automatic scaffold that moves vertically while horizontally feeding rebar into place. It both speeds the process and reduces labour requirements. Figure IV-13 shows a machine that automatically assembles rebar according to instructions from a 3-dimensional computer design model.

FIG. IV-12. An automatic scaffold and horizontal rebar feeding machine at Kashiwazaki Kariwa-6 in Japan.

IV-7. Advanced concrete composition

In addition to these advanced methods for pouring and installing concrete, there have been recent advances in the composition of concrete to improve strength, workability, and corrosion resistance. Examples are self-compacting concrete, high performance concrete and reactive powder

FIG. IV-13. An automatic rebar assembly machine at Kashiwazaki Kariwa-7 in Japan.

concrete. These are used not only in nuclear power plants but in other large civil projects such as bridges, highway, large buildings and dams.

IV-8. All weather construction and working around the clock

To ensure that work can continue in all weather conditions, an all weather cover dome can be put over the reactor building. This method was used, for example, at Kashiwazaki-Kariwa-6 in Japan.

Working around the clock, both indoors and outdoors (see Fig. IV-14), can save considerable time at critical stages of construction, for example during excavation, concrete pouring, structural steel erection, calandria vault construction and various welding activities.

IV-9. Bending small bore pipes to reduce welding requirements

For small bore pipes, elbow fittings and their associated welds can be eliminated by forming bends within pipe lengths. Although the bending operation introduces costs of its own, the benefits include time and labour

FIG. IV-14. Night view of site activities at Tarapur-4 in India.

savings through reduced welding requirements and, because there are fewer welds to be inspected later, reduced inspection requirements.

IV-10. Advanced excavation methods

Advances in excavation that can be applied to nuclear power plants include new equipment, such as large excavators designed for heavy workloads, massive grading and material handling, and large equipment for vibratory soil compacting. They also include precision blasting for excavating rock, which can reduce costs relative to more conventional mechanical excavation methods, for the reactor building, turbine building and other buildings. Several shafts are drilled in a precise pattern in the required area to be excavated and filled with explosives, which are then detonated. The possibility of using precision blasting depends on a site's geology and the plant's design as well as applicable regulations governing blasting.

IV-11. Cable installation

The installation of cables takes a significant amount of time and can be part of the critical path. 'Cable pulling' is the term used for the process of installing cables in cable trays (conduits) to connect plant equipment to power sources. The conventional method involves applying a lubricant to a cable (or group of cables) and pulling them into place with a rope. Improvements in this method involve better lubricants and cable rollers. Another technique reduces the need for cable pulling by splicing together the ends of cables that pass through different modules. Such splicing techniques are well established in the ship building industry.

IV-12. Area completion schedule management

The area completion schedule management method has been applied in the Republic of Korea at Shin-Kori-1 and -2. This approach replaces design and procurement schedules that used to progress system by system or, for a given building, floor by floor with an approach that divides each level of each building into zones. This allows more detailed scheduling of material purchase and the issuance of construction drawings to best integrate requirements in all zones. The approach is also used to schedule integrated installation work and set priorities among civil, mechanical, electrical and other needed work in each zone.

IV-13. Computer systems for information management and control

The use of computer systems for information management and control is well established in the design, engineering and construction of large projects including power plants. For nuclear power plants the design and construction information must be maintained throughout the life of the plant including decommissioning. Computerized databases centralize all design information and allow quick access by all parties to design and construction drawings, equipment specifications, and inspection and testing data. The benefits of computerized information management and control systems are that they improve productivity through concurrent engineering, procurement and construction; allow drawings to be revised and accessed electronically; facilitate accurate determination of material quantities; and facilitate efficient procurement and construction management.

Such integrated systems can be used to develop 3-D models of:

- Engineered piping and in-line piping components such as valves and strainers;
- Raceways;
- Structural steel;
- Concrete;
- Heating, air conditioning and ventilation components;
- Equipment (tanks, pumps, heat exchangers, etc.);
- Piping supports;
- Piping and instrumentation diagrams;
- Embedded parts and plates.

Such 3-D computer models can then be linked to the schedule to provide ‘4-D modelling’. Specific deliverables at any stage can be extracted from the computer assisted design drawing model, including piping system isometric drawings, general arrangement drawings, and materials quantities, and the overall installation plan can be more easily visualized. During operation such models can be used to train operators and system engineers and to help nuclear safety engineers to visualize systems when evaluating performance and safety issues. For nuclear power plants, the system can also be expanded to track the inspections, tests, analyses and acceptance criteria that must be applied during construction to meet regulatory requirements.

IV-14. Summary

The construction methods available for new nuclear power plants are generally the same as those used for other large construction projects. There have been numerous improvements in construction methods in the past few years, and recent experience in nuclear power plant construction has shown that those advanced methods are fully applicable and can help shorten construction schedules. Recent nuclear construction projects have been completed in as little as four years. The decision to apply some of these methods must be made in the conceptual design stage and then followed through consistently. Some advanced construction methods require earlier investments for factories and workshops and earlier outlays of funds to purchase materials, although they later save time and labour. Thus a shorter schedule does not necessarily mean lower total costs, and the relative costs and benefits for each of the methods summarized here must be weighed for each project independently.

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Annex V

INTERFACING NUCLEAR POWER PLANTS WITH THE ELECTRIC GRID: THE NEED FOR RELIABILITY AMID COMPLEXIty

V-1. Introduction

For a country that does not yet use nuclear power, the introduction and development of nuclear power is a major undertaking. It requires the country to build the necessary infrastructure so it can construct and operate a nuclear power plant (NPP) profitably in a safe, secure and technically sound manner. A major part of the necessary infrastructure is the electric grid to which the NPP will connect. While most countries already have an electric grid system, it may require significant development to be suitable for the connection of an NPP. The efficient, safe, secure and reliable operation of the NPP requires that the grid to which it connects is also efficient, safe, secure and reliable. This annex explains the characteristics of the electric grid, its relationship with the NPP, and the reasons why a reliable grid is so important to the NPP.

The grid is the electrical highway through which all electricity traffic passes as it moves energy from the supplier ('generation') to the customer ('load'). Interconnected electric grids can encompass several countries and are probably the largest machines in the world. They consist of hundreds of power suppliers, thousands of kilometres of transmission and distribution lines and millions of different electrical loads. Rapid economic development in the 20th century made the electric grid system a critical part of the economic infrastructure in industrialized countries and a permanent feature of the landscape.

NPPs are unique and powerful generators compared to other electricity generating plants. Moreover, they are both electricity generators and customers. They thus maintain a symbiotic relationship with the electric grid at all times. NPPs supply large amounts of energy to the grid as well as relying on it to receive power for crucial safety operations, especially during emergency conditions. The safe startup, operation and shutdown of NPPs require a reliable and stable power supply from the electric grid, referred to generally as 'off-site power'.

The grid's principal function is to transport electricity from the power plant to customers. But it does much more than that. A reliable, balanced and well maintained electric grid is crucial for bringing new nuclear power plants online and operating them cost effectively and safely. In particular, the grid plays an important safety role by providing a reliable source of electricity to power the plant's cooling system to keep nuclear fuel cool after a reactor has been shut down (although NPPs also have on-site back-up power available for emergency situations). The fewer instabilities and interruptions there are in NPP–grid interactions, the more productively and consistently the NPP can supply full power to consumers. Siting decisions must therefore take into account the local grid conditions and usage, and, because of the grid's role in plant safety as well as plant economics, integration of NPPs into an electric grid poses a complex set of regulatory as well as engineering challenges.

Countries expanding or introducing nuclear power programmes are advised to consider their electric grids as part of their planning process, particularly as the grid impacts the size and type of reactor that can be deployed. Specific issues that should be considered in the early phases of a nuclear power programme include grid capacity and future growth, historical stability and reliability, and the potential for local and regional interconnections. Assessment of the current grid and plans for improving the grid should therefore be developed to be consistent with plans for nuclear power.

V-2. Vulnerability of the electric grid

The grid must maintain a precise frequency of alternating current; a relatively small imprecision can cause disproportionate damage. The electric power received at a house or a factory is the result of hundreds of distant, widely dispersed generators sending electricity through a maze of circuits, wires and transformers, and under varying weather conditions, at a single synchronized precise frequency without missing a beat.

Section G.1 describes how such synchronization is normally maintained, but this section outlines what can happen when things go wrong. Even a well balanced grid is subject to events that can potentially lead to large scale disturbances or even to a collapse of the grid if the grid operates near its capacity with no margin for faults. A small shift of power flows caused by a sudden increase or decrease of electricity generation or the load can trip protective circuit breakers which send larger power flows to neighbouring power lines, possibly triggering a chain reaction of failures.

The grid systems in developed countries are normally designed and operated with a contingency margin. They are operated so that no single fault on the system can lead to unacceptable problems such as abnormal voltage, abnormal frequency or disconnection of demand. However, if this margin is not maintained, or multiple faults happen close together in time, a major failure can still occur.

Much of the north-eastern United States of America and part of Canada were plunged into darkness in August 2003 when a disruption in the electric grid's intricate balance caused a massive blackout (Fig. V-1) with substantial economic consequences. This was an example of cascading events resulting in the complete shutdown of the grid. The blackout affected an estimated 10 million people in Ontario and 40 million people in eight US States.

The collapse of the grid was caused in this case by a combination of human errors and technical challenges: power plant outages, overextended controllers, transmission line failures, the overheating of alternate transmission lines causing lines to sag into trees, an insufficient ability to repair or replace sensors and relays quickly, poor maintenance of control room alarms, poor communications between load dispatchers and power plant operators, insufficient understanding of transmission system interdependencies, and the grid operating very near its transmission capacity. As a consequence, nine NPPs in the USA and eleven NPPs in Canada were disconnected from the grid because of electrical instabilities.

The North American blackout was in fact only one of seven blackouts in a six week period in 2003 that affected more than 120 million people in eight countries: Canada, Denmark, Finland, Italy, Malaysia, Sweden, the United Kingdom and the USA. In Sweden, in September, a nuclear power plant tripped (i.e. rapidly shut down), resulting in the loss of 1200 MW(e) to the grid. Five minutes later a grid failure caused the shutdown of two units at another

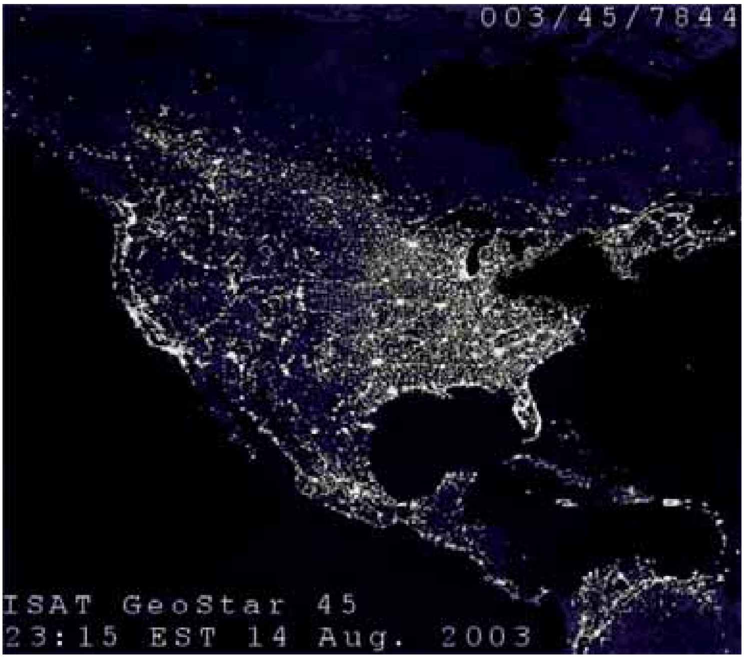

FIG. V-1. Blackout in the north-eastern USA and Ontario, Canada, August 2003.

nuclear power plant with the loss of a further 1800 MW(e). To respond to this loss of 3000 MW(e) (about 20% of Sweden's electricity consumption) the grid operators isolated the southern Sweden–eastern Denmark section of the grid, but the voltage eventually collapsed due to the insufficient power supply. At the time of the original reactor trip two high-voltage transmission lines and three links to neighbouring countries were out of service for normal maintenance work and four nuclear units were off-line for annual overhauls. Their unavailability severely limited the options of the grid operators.

Electric grids are also vulnerable to natural disasters such as tornadoes, hurricanes, earthquakes and ice storms. One well known example is the North American ice storm of 1998. In January 1998, a massive ice storm struck a relatively narrow area from eastern Ontario via southern Quebec to Nova Scotia in Canada as well as bordering areas from northern New York to south-eastern Maine in the USA. Freezing rain coated the area with 7–11 cm of ice. It caused massive damage to trees and power lines throughout the area, leading to widespread long term power outages (Fig. V-2). Trees and electrical wires fell, and utility poles and transmission towers came down causing massive power outages, some for as long as one month. It was the most expensive natural disaster in Canada. Over four million people in Ontario, Quebec and New Brunswick lost power. Some 130 power transmission towers were destroyed, and more than 30 000 utility poles fell.

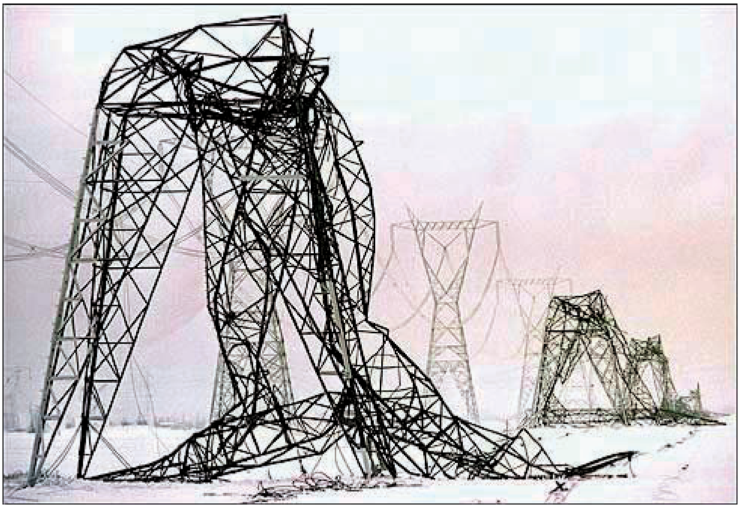

FIG. V-2. Freezing rain caused extensive damage to transmission lines in Quebec, Canada, in January 1998.

V-3. Structure of the electric grid

The electric grid consists of two separate infrastructures. The electric power lines that are most visible are the high voltage transmission system carrying electricity for large distances with relatively low current. Electricity is generated by power plants at a relatively low voltage (ranging from 2 kV to 50 kV, depending on the size of the power station) and must be transformed into high voltage electricity by step-up transformers at the stations' switchyards. The high voltage (from 100 kV to 800 kV) allows the transmission lines to carry electric power at low current, therefore minimizing electrical losses over long distances. Losses in electricity are generally due to the electrical resistance and consequent heating of the cables. Typical losses for the United Kingdom and the USA are around 7% of the energy passed through the transmission and distribution networks.

The second system is the low voltage distribution system that draws electricity from the high voltage transmission lines and distributes it to individual customers. At the interface between the high voltage transmission lines and the distribution systems, an electrical substation uses transformers to 'step down' the transmission line voltage to the lower voltage of the distribution system. Substations also include electrical switches and circuit breakers to protect the transformers and the transmission system from electrical failures on the distribution lines. Transformers are located along the distribution lines to further step down the line voltage for household use (120–380 V) and are protected by circuit breakers that locally isolate electrical problems, such as short circuits caused by downed power lines.

The transmission grid, with multiple generating stations and distribution system connections, functions as one entity potentially stretching for thousands of kilometres. Physically and administratively divided smaller networks are often connected together forming a large electric grid. For example, in North America there are three loosely coupled networks covering the USA and Canada (Fig. V-3). Within each network, power flows through alternating current (AC) lines, and all power generators are tightly synchronized to the same cycle in terms of frequency. The three networks are joined by transmission lines carrying direct current (DC), so the coupling and the need for frequency and phase synchronization are more relaxed than within the individual networks. The capacity of the DC transmission lines connecting the networks is also much less than that of the AC transmission lines within them.

In North America, prior to electricity deregulation, regional and local electric utilities were regulated vertical monopolies. A single company

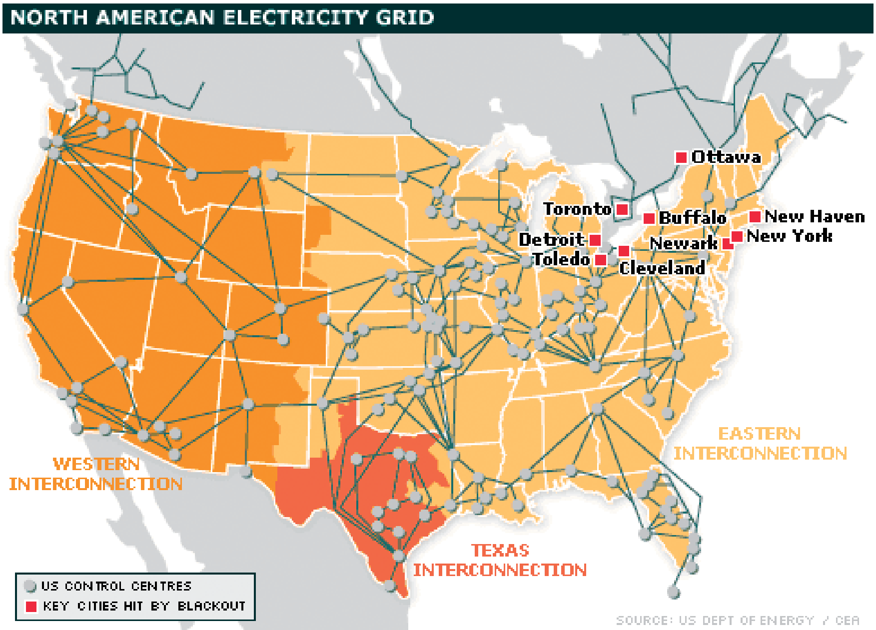

FIG. V-3. Electric grids covering the USA and Canada.

controlled electricity generation, transmission, and distribution in a given geographical area. Each utility generally maintained sufficient generation capacity to meet its customers' needs in its service area, and long distance energy shipments were usually reserved for emergencies, such as unexpected generation outages and transmission line failures. In essence, the long range connections served as insurance against a sudden loss of power. This limited the use of long distance connections to aid system reliability because the physical complexities of power transmission rise rapidly as distance and the complexity of interconnections grow.

V-4. Grid operation

Stability in the grid system is maintained by matching the electricity generation with the ever changing demand. The electricity from many power generating stations is 'pooled' in the transmission system, and each customer draws from this pool. Power entering the system flows along all available paths to the distribution systems. This pooling of electricity also means that power is provided from a variety of generating stations of different sizes, including nuclear, coal, oil, natural gas and renewable energy sources such as wind, solar, biomass and hydropower, which must all be synchronized to the same 'rhythm' with millisecond accuracy. For a power grid to remain stable, the frequency and phase of all power generation units must remain synchronous within narrow limits. A generator that loses synchronism with other generators but stays connected to the grid will experience large electrical currents, which will lead to overheating and large mechanical forces that will rapidly destroy the generator. So protective circuit breakers disconnect (trip) a generator from the grid when the generator loses synchronism.

Electric power takes the path of least impedance from its source to the load, which generally means the shortest route but may also include parallel flow paths through other parts of the system. When a utility agrees to send electricity to a customer, the utility increases the amount of power generated while the customer increases its load. The power then flows from the utility to the customer along as many of the paths that connect them as it needs to make the trip with the least impedance possible. This means that changes in generation and transmission at any point in the system will change loads on generators and transmission at every other point, which is not easily controlled. To avoid system failures, the amount of power flowing through each transmission line must remain below the line's capacity. Exceeding capacity can cause overheating. Overhead lines which overheat will sag, and may cause electrical flashover to trees or the ground. Underground cables which overheat can damage their insulation. Exceeding capacity can also create power supply instability such as phase and voltage fluctuations.

The transmission grid, with multiple generating stations and distribution system connections, functions as one entity potentially stretching for thousands of kilometres. The grid must accommodate changing electricity supply and demand conditions, planned or unexpected outages of generating stations, transmission lines, and customers, as well as extreme weather conditions. The balance between electricity supply and demand must be maintained at any time by increasing or decreasing the output of the operating power plants or turning power plants on or off. Nuclear power plants are rarely operated in this 'load following' mode. Rather they provide a constant 'baseload' supply of electricity to the grid. Thus having a baseload nuclear plant on a grid means that other plants must be 'load following', i.e. able to increase or decrease their output to balance changes in electricity demand.

V-5. Interfacing nuclear power plants with electric grids

Both nuclear power plants and electric transmission grids (Fig. V-4) are fascinating engineering achievements on their own. When they are connected together in a highly controlled, dynamic and distributed network, further complexity is created. This complexity of engineered systems is a consequence of several factors: the sheer size and interconnectivity of the electric grid, the nuclear safety requirements imposed on NPPs, the need to balance electricity supply and consumption throughout the grid at all times, and the nature of electricity — that it is generated as it is used. Unlike other commodities, it is difficult to store electricity. This means the electric grid system requires continual surveillance and adjustment to ensure supply always matches demand. Unlike nuclear power plants, the inherent, natural and passive safety feedback systems based on physical laws are rather weak. Hence electric grids require continuous control and balancing actions based on engineered systems.

Nuclear power plants are operated usually in baseload mode (i.e. steady state operation at full power) and less frequently in load following mode. The integration of large NPPs into an electric grid brings nuclear safety requirements that impose additional requirements on the grid design, operation and stability. Specifically, when NPPs are not generating electricity, they, like other power plants, still need electricity from the grid to support maintenance work, operate other equipment, keep the plant ready to restart, and, very importantly, operate critical safety systems. In NPPs the source of energy (the nuclear chain reaction) can be turned off in a few seconds. However, significant heat is still generated from the long term decay of highly radioactive fission products. This residual heat has to be removed from the reactor core indefinitely in order to prevent overheating of the reactor fuel and its consequent damage. The reactor cooling systems must be therefore powered by a long term stable source of electricity. In addition, to prevent fuel rod damage, sufficient and reliable power is needed to maintain conditions in the coolant system and containment and to run vital safety related instrumentation, control, monitoring and surveillance systems. Electric power is also needed for heating, ventilation and air conditioning (HVAC) systems used for assuring operable environments for equipment and personnel. This stable source of power comes either from the grid (off-site power), or from on-site emergency back-up power, such as batteries, diesel generators or gas turbines.

The reliability of off-site power is usually assured by two or more physically independent transmission circuits to the NPP to minimize the likelihood of their simultaneous failure. Similarly, the reliability of on-site power is enhanced by sufficient independence, redundancy and testability of batteries, diesel generators, gas turbines and the on-site electric distribution systems to perform safety and other functions even if a single failure occurs. Because of the importance of reliable off-site power as well as considerations of cost effectiveness and efficiency, the electric grid is an important factor in NPP site selection, which must take into account the plant's position within the

FIG. V-4. Power lines coming into the Callaway NPP.

grid as well as its proximity to centres of electricity demand, population density and other factors.

In addition to assuring that the electric grid will provide reliable off-site power to NPPs, there are other important factors to consider when an NPP will be the first nuclear unit on the grid and, most likely, the largest unit. If an NPP is too large for a given grid, the operators of the NPP and the grid may face several problems.

- Off-peak electricity demand might be too low for a large NPP to be operated in baseload mode, i.e. at constant full power.
- There must be enough reserve generating capacity in the grid to ensure grid stability during the NPP's planned outages for refuelling and maintenance.
- Any unexpected sudden disconnect of the NPP from an otherwise stable electric grid could trigger a severe imbalance between power generation and consumption causing a sudden reduction in grid frequency and voltage. This could even cascade into the collapse of the grid if additional power sources are not connected to the grid in time.

V-6. Operational modes of nuclear power plants

Most NPPs are baseload plants operating normally at 100% power. Startup, shutdown and load changes are very infrequent, usually dictated by NPP requirements such as refuelling, inspections and internal restrictions. Baseload operation of NPPs is more economic for the system as a whole because fuel costs are lower for NPPs than for fossil fuel plants and because turning NPPs off and on is more complex and expensive than it is for fossil fuel plants. However, there may be other reasons to consider some operational flexibility and load following for an NPP. For example, in a developing country with a small grid, off-peak electricity demand may be too low for baseload operation, or NPPs may need to do some load following as the share of nuclear power is increased by additional NPPs coming on line.

NPPs operating in a load following mode can be further divided into two categories. Firstly, scheduled load following plants that normally operate at 100% power but may, at certain predetermined times, operate at partial power according to grid requirements. These plants can follow a predetermined daily pattern, e.g. operating at 100% power for 12 hours, then, over the next three hours, reducing to 50% power, operating at 50% power for six hours, and then increasing back up to 100% over the next three hours. Secondly, arbitrary load following plants that operate in their upper power range and are expected to meet the daily grid load requirements, including rapid power changes of up to 10% per minute. Some disadvantages of operating NPPs in a load following mode are that plant components will be exposed to many thermal stress cycles and that more sophisticated instrumentation and control systems will be needed. Both add costs.

V-7. Disturbances affecting the interaction between nuclear power plants and electric grids

Grid interconnectivity and redundancies in transmission paths and generating sources are key elements in maintaining reliability and stability in high performance grids. However, operational disturbances can still occur even in well maintained grids. Similarly, even an NPP running in baseload steady state conditions can encounter unexpected operating conditions that may cause transients or a complete shutdown in the plant's electrical generation. When relatively large NPPs are connected to the electric grid, abnormalities occurring in either can lead to the shutdown or collapse of the other.

The technical issues associated with the interface between NPPs and the electric grid include:

- The magnitude and frequency of load rejections and the loss of load to NPPs.
- Grid transients causing degraded voltage and frequency in the power supply of key safety and operational systems of NPPs.
- A complete loss of off-site power to an NPP due to grid disturbances.
- An NPP unit trip causing a grid disturbance resulting in severe degradation of the grid voltage and frequency, or even to the collapse of the power grid.

V-8. Influence of grid disturbances on nuclear power plants

V-8.1. Load rejection and complete loss of load

A load rejection is a sudden reduction in the electric power demanded by the grid. Such a reduction might be caused by the sudden opening of an interconnection with another part of the grid that has carried a large load. An NPP is designed to withstand load rejections up to a certain limit without tripping the reactor. An NPP's ability to cope with a load rejection depends on how fast the reactor power can be reduced without tripping and then how fast the reactor power output can be increased back to the original level when the fault is cleared. Load rejections of up to 50% are accommodated by a combination of several actions: rapidly running back the steam turbine to the new lower demand level, diverting the excess steam from the turbine to the main steam condenser unit or to the atmosphere if this is permitted by licensing regulations, and reducing reactor power via insertion of control rods without tripping the reactor.

A *loss of load* is a 100% load rejection, that is, the entire external load connected to the power station is suddenly lost, or the breaker at the station's generator output is opened. Under this severe condition, it may still be possible to 'island' the NPP so that it powers only its own auxiliary systems. During this 'house-load' operating mode, the reactor operates at a reduced power level that is still sufficient to assure enough electricity for its own needs, typically 5% of full power. Once the grid disturbance has been eliminated, the NPP can be re-synchronized to the grid and its production quickly raised again to full power. This operational characteristic of the NPP is important when the loss of load is expected to last for just a short time.

V-9. Degraded grid voltage or frequency

Electric grids are controlled to assure that a particular frequency, either 50 or 60 Hz, is maintained within a small tolerance, typically within ±1%. When the grid develops an imbalance between generation and load, the grid frequency tends to 'droop' if the load exceeds generation and increase if generation exceeds the load. A reduction in frequency can be caused by several events, such as insufficient available generation, a major electrical disturbance such as a circuit fault, or the trip of a major generator unit. A small droop in the grid frequency caused by the loss of generation can be controlled by:

- Quickly activating the grid's available 'spinning reserve'[30], either automatically or manually,
- Starting up additional generation capacity, such as gas turbines or hydroelectric power, and
- Disconnecting selected loads (i.e. customers) from the grid (load shedding).

Isolating the section of the grid with the NPP from the rest of the grid ('system islanding') can also help maintain the proper frequency in the islanded system. System islanding may reduce the load on the NPP, requiring that its generation be reduced accordingly by a quick set-back to an intermediate power level. Proper islanding prevents the NPP from tripping because of the lower frequency, but may further aggravate the power imbalance in the rest of the grid. A plant trip including reactor shutdown should be regarded as a last resort. During a trip the plant is subject to rapid changes in power, pressure and temperature, which shorten the lifetime of the plant. Moreover, if the NPP is immediately disconnected from the grid, the lost generation will exacerbate the already degraded conditions on the grid.

Any change in the grid frequency affects an NPP's operation by changing the speed of the NPP's turbogenerator and the speed of pumps circulating coolants through the reactor and the secondary coolant circuits. The main reactor circulating pumps, steam generator feedwater pumps and long term decay heat removal systems rely on stable electric power to function properly. The speed of the reactor's main coolant pumps is directly proportional to the frequency of the electric power supply. Therefore, if the frequency of the power from the grid drops far enough, the pumps will slow, which will lead to inadequate core cooling, and the reactor will trip.

Other AC motors in the NPP may also trip due to rising currents and consequent overheating caused by reduced frequency. The performance of AC

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[30] Spinning reserve is any unused capacity that is already connected and synchronized to the grid ('spinning') and can be activated immediately on the decision of the grid operator, reaching its full capacity within ten minutes.

motors is directly affected by the voltage and frequency of their power supplies. If electric grid voltages are not sufficient, motors cannot develop sufficient motor torque to start, and if the frequency drops below a certain value, the start and operation of AC motors would require higher operating voltages. If the voltage is insufficient, it results in excessive current being drawn by the motor that in return would lead to overheating and the opening of protective breakers.

The frequency and voltage ranges in which large AC motors can operate are relatively narrow. Thus, in severely abnormal conditions, safety systems in nuclear power plants are required to take protective actions such as tripping the reactor and turbine, separating the plant electrical systems from the degraded conditions present on the grid, and switching to on-site emergency power sources until the grid voltage and frequency are restored to acceptable values. These actions protect the NPP by safely shutting it down and keeping it cooled. However, any sudden automatic shutdown of a large baseload nuclear unit during periods where there is already a mismatch between generation and load on the grid can only further degrade the grid's condition, potentially leading to a partial or full collapse.

V-10. Loss of off-site power

Any loss of off-site power would be caused by external events beyond the NPP's switchyard, such as transmission line faults and weather effects like lightning strikes, ice storms and hurricanes. A loss of off-site power interrupts power to all in-plant loads such as pumps and motors, and to the NPP's safety systems. As a protective action, safety systems will trigger multiple commands for reactor protective trips (e.g. turbine and generator trip, low coolant flow trip, and loss of feedwater flow trip). The reactor protection system will also attempt to switch to an alternate off-site power source to remove residual heat from the reactor core. If this fails, in-plant electrical loads must be temporarily powered by batteries and stand-by diesel generators until off-site power is restored. However, diesel generators may not be as reliable as off-site power from the grid in normal conditions. Diesel generators may fail to start or run 1% of the time. However, the probability of failure can be significantly reduced by installing independent trains of diesel generators. Batteries can provide power only for a limited time.

V-11. Influence of NPP disturbances on the grid

V-11.1. Trip of an NPP causing degraded grid frequency and voltage

Even at steady state conditions, when the generation and loads on a grid are in balance, if a large NPP (e.g. 10% of the grid's total generating capacity) trips unexpectedly, the result can be a significant mismatch between generation and load on the grid. Unless additional power sources are quickly connected to the grid, this can degrade the grid's voltage and frequency and thus the off-site power supply to the NPP. As discussed in Section G.1, degraded voltage and frequency on the grid can potentially result in the NPP protection system disconnecting the degraded off-site power to the NPP. This will force the NPP to switch to on-site emergency power to run safety and core cooling systems until off-site power is restored. This should be done as soon as possible for safety reasons: the possible concurrent failure of the NPP's on-site power system and delayed recovery of off-site electric power would make it nearly impossible in most NPPs to cool the core, a situation that must be avoided under all conditions. The introduction of new reactor designs that use passive cooling would alleviate this problem. Therefore, in unreliable grid systems, it is recommended to consider NPP designs with passive safety systems.

The grid's response over time to the sudden loss of the NPP can be modelled by computer simulations, conditioned by the capacity and interconnectivity of the grid and the size of the lost NPP generation, as well as the timing of switching additional power sources to the grid. Large interconnected electric grids can usually meet the requirement of providing reliable off-site power to NPPs connected to the grid. However, in some scenarios involving poorly interconnected or controlled electric grids, the sudden shutdown of a large NPP, or any other large generating station elsewhere on the grid, might result in severe degradation of the grid's voltage and frequency, or even to the collapse of the overall power grid. Similarly, when an NPP is sited on a well maintained but small and isolated grid of limited generating capacity (e.g. on an island), the sudden loss of its generation may lead to the same outcome.

Complex computer models are used to decide whether the loss of the largest operating unit on the grid could result in the loss of grid stability and of off-site power. In simulation studies, the consequences of various single faults (e.g. the sudden loss of key transmission lines or a power generating unit) are explored. The output of the simulations provides the time dependent response of the grid (in terms of voltage and frequency) to the event, including protective actions, such as automatic load shedding, emergency disconnects and starting up additional power sources that can start quickly.

Results show that isolated grids are inherently less stable than equivalent grids of the same size with supporting grid interconnections. Therefore the design and licensing basis for 'poorly sited' NPPs should include provisions for more reliable on-site power, i.e. additional capacity for the on-site power system beyond the normal requirements (e.g. more diesel generators and fast-starting gas turbine engines). This would compensate for less reliable off-site power by providing more reliable on-site power, and it would assure that the degradation or collapse of the grid would not make an NPP's decay heat removal systems inoperable.

V-12. Conclusions

As noted at the outset, countries expanding or introducing nuclear power programmes are advised to consider their electric grids as part of their planning process:

- The electric grid should provide reliable off-site power to NPPs with a stable frequency and voltage.
- Any potential lack of reliability in off-site power from the grid must be compensated for by increased reliability of on-site power sources.
- Enough reserve generating capacity should be available to ensure grid stability to replace NPP generation during planned NPP outages.
- The grid should also have a sufficient 'spinning reserve' and standby generation capacity that can be quickly brought online in case the NPP were to be disconnected unexpectedly from the grid.
- The off-peak electricity demand should preferably be large enough for the NPP to be operated in a baseload mode at constant full power.
- If there is any possibility of the NPP being operated in a load following mode, any additional design requirements to ensure safe load following operation should be discussed in advance with the NPP designer or vendor company.
- If baseload operation will not be possible, the NPP should have additional design margins to compensate for the increased exposure to thermal stress cycles, and more sophisticated instrumentation and control systems.
- The national grid should have enough interconnections with neighbouring grids to enable the transfer of large amounts of electricity in case it is needed to offset unexpected imbalances of generation and demand.
- In preparation for the introduction of an NPP, if grid reliability and the frequency and voltage stability of the existing grid are insufficient, they should be made sufficient before the NPP is brought online. Any

improvements will not only allow the grid to incorporate the new NPP but will have additional benefits for all customers and other generators.

- Communication is critical, in this case between the NPP operators and grid dispatchers. Effective communication protocols will need to be developed.

Annex VI

SEEKING SUSTAINABLE CLIMATE, LAND, ENERGY AND WATER (CLEW) STRATEGIES

VI-1. Introduction

Given growing global demands, the world's resources of water, land and energy are relatively scarce; the use of each affects demand for the others; and the use of all affects the climate. There are 1.1 billion people without safe water and 1.6 billion without electricity [VI-1]. The need for more cultivated land drives deforestation. Energy prices are high, and anthropogenic greenhouse gas emissions (GHGs) continue to rise. High oil prices in turn mean high transport costs. Those, together with biofuel crops competing with food crops for land, recently caused food prices to spike beyond the reach of many of the world's poor — a trend some analysts do not see abating [VI-2].

These interdependencies mean that energy policies based on energy analyses alone, for example, might have adverse unanticipated effects on water resources, land resources and the climate. The same is true for water policies based only on analyses of water issues, and for land policies based only on land-use analyses. Better methods and models are therefore needed that consider all the linkages among climate, land, energy and water (CLEW). This annex analyses that need by reviewing the models available today, by summarizing examples where they fall short, by reviewing the history and remaining challenges of 'systems approaches', and by outlining a way forward.

The specific focus is on the expansion of a systems approach to underpin the analysis of sustainable development with an emphasis on CLEW resources. Analyses of individual systems such as energy and water systems are undertaken routinely. The IAEA provides and supports detailed analyses of a country's or region's energy system with the MESSAGE model[31]. A commonly used model for water planning is the Water Evaluation and Planning system

[31] MESSAGE (Model of Energy Supply Systems and their General Environmental Impacts) is a systems engineering optimization model which can be used for medium to long term energy system planning, energy policy analysis and scenario development. The model provides a framework for representing an energy system with its internal interdependencies [VI-3].

(WEAP[32]), and for water scarcity and food security planning, the Global Policy Dialogue Model (PODIUM) is well established[33]. However, these and other models are, in one way or another, all lacking, especially if one wants to use them for policy analysis for developing countries. Generally, they either focus on one resource and ignore interconnections with other resources, have overly simplified spatial representations or analyse scenarios which are impractically long term.

What is needed is an integrated analysis tool that includes all CLEW aspects in a manner that is accessible and useful to analysts and planners in developing countries. Key improvements over existing approaches should include: finer geographical coverage, simplified data requirements, a medium term temporal scope, multi-resource representation (including their inter-linkages) and software accessible to developing country analysts. Such a tool would help decision makers assess different technological options with diverse benefits and disadvantages; estimate the impacts of different development scenarios; and analyse and evaluate policies.

The IAEA is ideally suited to develop such an integrated tool by virtue of its expertise in a number of key areas, such as energy systems planning[34], water resources and isotope hydrology[35], nuclear desalination[36], and food and agriculture in cooperation with the FAO[37]. The Agency also has a strong mandate as part of the UN system to support Member States, through its technical cooperation programme[38], in their development and implementation of strategies for sustainable development. In particular, Member States have clearly and frequently articulated their concerns about sufficient water supplies, food security and energy security[39]. However, the IAEA's current assistance is necessarily limited and compartmentalized. An effort such as this will help better meet the needs of Member States, drawing on significant existing in-house capacity. Further, it is envisaged that after initial incubation of

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[32] The WEAP energy model is maintained and supported by the Stockholm Environmental Institute: http://www.weap21.org/

[33] PODIUM is maintained and supported by the International Water Management Institute http://podium.iwmi.org/podium/

[34] http://www.iaea.org/OurWork/ST/NE/Pess/

[35] http://www.iaea.org/programmes/ripc/ih/

[36] http://www.iaea.org/OurWork/ST/NE/NENP/Desalination/

[37] http://www-naweb.iaea.org/nafa/index.html

[38] http://wwwtc.iaea.org/tcgc/gc/gcstart.html

[39] See for example the recently completed Country Program Framework (CPF) of Cameroon, 2009–2013, and others.

the concept within the IAEA, consultation with other experts and agencies in the UN system will take place.

The next section briefly summarizes key past examples of related modelling efforts, presents some motivating examples of uncoordinated development, and introduces the challenges faced by policy makers. The subsequent sections discuss aspects of the CLEW system and suggest a simple integrated framework and goals for a systems tool.

VI-2. Modelling the CLEW systems

While the proposed tool will be unique and designed specifically to better meet the needs of IAEA Member States, it will build on previous work and an established methodological approach.

The most famous systems analysis to address some of the CLEW issues was the study *The Limits to Growth*[40] in the early 1970s [VI-4]. While providing important insights, the analysis was of little use to national policy makers because it had a very coarse geographical resolution in that it modelled the world as a whole, rather than a country or local area; it did not account for changes in technology, knowledge or behaviour; and it did not account adequately for the effects of price changes. A second approach, developed around the same time to analyse the provision of energy services, focused on five connected resources: water, energy, land, materials and manpower (WELMM) [VI-5]. However, this approach was never developed into a manageable software package that could be used by national analysts.

Since then a large range of planning models, which, to lesser or greater extents, overcome those limits, have been developed and applied regularly. However, these are generally focused only on a single resource, such as water, land or energy[41]. Integrated assessment models attempt to include more aspects of the CLEW system, but these are aggregate, focused at the global or regional level, and often designed for long term analysis. They are not useful for medium term national analysis[42]. Further they can be limited by requiring data and computational support beyond the reach of local analysts in some developing countries.

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[40] In 1981, another global study, focused specifically on energy issues, was published by the International Institute for Applied Systems Analysis (IIASA) under the title *Energy in a Finite World* [VI-6].

[41] A notable exception is the (albeit limited) combined energy and water planning being undertaken within certain US districts [VI-7].

[42] Examples include MINICAM [VI-8], IMAGE [VI-9] and TIAM [VI-10].

The 'systems approach' referred to in this annex is extensively used (although its application to CLEW is still missing). It refers to a physical accounting of resource, technology and other requirements to meet certain needs and services, with the accounting extended far upstream. For example, water, crop, fertilizer and land requirements can be calculated for a given food production level. Each of these inputs in turn requires its own inputs, which are also accounted for. Fertilizer, for example, requires transport and production, both of which require energy, water and technologies and emit greenhouse gases. In turn, those energy and water inputs are associated with their own inputs, technologies and emissions, etc. The accounting continues until satisfactory estimates of resource and other needs, as well as impacts, are calculated. In some instances, the proposed development path may prove to be limited by resource constraints, in which case an alternative can be investigated.

At each step in the systems approach, costs can be calculated, and a systems model can be programmed to identify which development path, given various constraints, is the most economic.

VI-3. Notable examples of CLEW challenges

The following examples of interconnected CLEW relationships highlight the need for integrated planning to meet energy, water and land related service requirements.

- Punjab has only 1.5% of **India**'s land, but its output of rice and wheat accounts for 50% of the grain the Government purchases and distributes to feed more than 400 million Indians. The problem is that farmers are pumping ('mining') aquifers faster than they can be replenished, and, as water levels drop, increased pumping is sapping an already fragile and overtaxed electricity grid. Moreover, because farmers in Punjab pay nothing for electricity, they run their pumps without stopping. This both further depletes the water table and, as water is pumped from ever increasing depths, requires ever more electricity to maintain a constant level of irrigation water [VI-11]. Overall, irrigation accounts for about 15–20% of India's total electricity use [VI-12]. The Government recognizes that all these issues are interconnected, but the planning does not.
- The United Nations Environment Programme (UNEP) expects the frequency of weather and climate extremes in **Colombia** to increase by 2050 [VI-13]. Regional impacts will include: changes in the composition of ecosystems and biome distribution; reduced water availability and hydropower generation; increasing desertification; aridity; crop pests and diseases. Colombia will face hydropower shortages caused partly by

increased El Niño events, which will force a further reduction in agricultural activity and, possibly, the future import of fuels for electricity generation. Such fuels are expensive, and, particularly in a volatile market, increased imports reduce the country's energy security.

- Uncoordinated development efforts in **Uganda** have slowed development and increased environmental stresses. Limited access to electricity (only 9% of Ugandans have electricity access) is a major drag on development, and major environmental problems include overgrazing, deforestation, and (often) low productivity agricultural methods, all of which lead to soil erosion. 93% of the country's energy needs are supplied by wood. The resulting deforestation is a severe problem, although its pace has slowed significantly, from a 67% loss of forests and woodlands between 1962 and 1977 to a 7.7% loss between 1983 and 1993. Wetlands have been drained for agricultural use, and the nation's water supply is threatened by toxic industrial pollutants. Mercury, for example, from mining has been found in the water supply. Roughly 20% of the urban population and 53% of the rural population do not have access to pure drinking water [VI-14]. Development is essential; coordinated development, urgent.
- **South Africa** is a semi-arid country. Ninety per cent of the country lies within arid, semi-arid or dry sub-humid zones. Yet the country is of key importance to Africa and its development. South Africa is the continent's largest exporter of agricultural products [VI-15] and requires large quantities of electricity to pump irrigation water. In addition, South Africa is a major electricity exporter, supplying over 40% of Africa's electricity. It is also an important exporter of international commodities, such as coal and gold, both of which consume substantial electricity in their production. But development is being retarded by inadequate investments in new electricity generating capacity. This supply shortage is estimated to cost the region billions of dollars as power shortages affect the international supply of commodities. Shortages in 2007, for example, forced gold prices to increase globally by 5% [VI-16]. As this was a result of a cost increase (rather than a demand increase), higher prices are likely to reduce sales and profit. Further, any increases in power supplies will require more water. Thus, if such increases are not coordinated with policies concerning other water uses, they may decrease water availability for such uses, including agriculture. On the other hand, expanding the cultivation of marginal lands for maize, together with overharvesting of fuel wood by the poor, are important causes of accelerated desertification. To address all of these issues, an integrated approach is clearly required.

- Global grain prices are volatile. Recent spikes were caused by many factors, including increased prices for fuel and thus transport, increased demand for **biofuels** driven by energy security and climate change concerns[43], as well as changing diets in populous fast growing developing countries. Diets that include more meat and more calories require substantially more land, both for livestock and for feed production. Increased feed production requires additional fertilizer and irrigation. Both fertilizer and irrigation (pumping) require energy, and if that energy is fossil fuel based, GHG emissions will increase. Moreover, as the demand for food, feed and biofuel grows, and as food requirements grow, so does the competition between the two for land. Similarly, there is competition between biofuels and food for fresh water and for fertilizers, especially as more marginal land is cultivated. Important positive impacts of increased biofuel production might include much needed economic opportunities for farmers and countries trapped by economic barriers. On the negative side it may cause short term opportunism, such as unsustainable clearing of forests for extra farmland, which may have long term consequences. Sorting out all the interconnections to provide useful insights for policy and decision makers requires better integrative analytical methods than are available today.

VI-4. Decision making and analysis

The intricate links among energy, water, land use, climate and other features of the environment, have been well documented for a long time, but governmental administrative structures tend to keep the management and development of these sectors separate from one another. Different ministries are usually responsible for energy, water and land, and any one of these is sometimes sub-divided among different administrative entities. For example, the responsibility for land use planning may be distributed among separate departments handling agriculture, forestry and urban development. As a result, there can be a lack of broad coherence, and, at times, decisions by one ministry or department can conflict with the objectives of others. Public policies can, therefore, be inadequately connected or researched. Energy supply options might be discussed with little reference to their water demands; water

[43] The actual impact of biofuels on climate change can be negative as well as positive, depending on the resulting land-use changes, and production, harvest and conversion methods. The need to analyse all these factors together reinforces the need for better methods and models that consider all the linkages among CLEW factors.

management options can be proposed without assessing their impacts on energy needs; land use development might be planned without thoroughly considering implications for energy and water; and the consequences for all these areas could be insufficiently considered in the light of longer-term climate policies.

A method for integrating local and national assessments would significantly improve information flows, and harmonize different departmental data collection, decision and policy making activities. Some assert that such a method is essential and that without such an integrated systems analysis tool, development, planning, policies and therefore development will not be sound and sustainable [VI-17 and VI-18].

VI-5. Goals

Given the desirability of a CLEW analysis and planning tool, it is important to clarify what the output of the tool should be. First, it should simulate, or account for, the CLEW system interactions both now and in the future. The primary target for its application should be developing Member States, and thus the tool should calculate the resource and service requirements to meet socio-economic goals — such as the Millennium Development Goals — in a growing economy. Thus, the tool should simulate important interactions within the CLEW system to meet energy, water and food related service demands, within constraints imposed by the physical and economic environments. In order to do this, a clear mapping should be made of relations within the CLEW system, and between it, other important resources and the economy.

In addition to incorporating such a mapping and quantification of key relationships, the tool should be designed for use in the following applications.

- Decision making: A well formulated integrated CLEW tool would help decision and policy makers assess options in terms of their likely effects on the broad CLEW system. The tool should be able to transparently evaluate the trade-offs reflected in different options.
- Policy assessments: Given limited resources, it is important for policy makers to ensure that policies are as cost-effective as possible. If multiple objectives can be achieved by a single policy, it may advance development more than policies focused separately on single objectives[44]. A CLEW

[44] See, for example Ref. [VI-19], which shows how different industrial energy efficiency options could affect water use, employment, GHG emissions and energy investment requirements. Analyses that consider the multiple benefits of each option will yield better estimates of the overall development potential of each.

tool should therefore provide a more complete, multi-system policy assessment.
- Facilitating policy harmonization and integration: In the examples in Section B.1 there are instances of very contradictory policies, e.g. electricity subsidies that accelerate aquifer depletion, which in turns lead to greater electricity use and subsidy requirements. A CLEW tool would help harmonize potentially conflicting policies.
- Technology assessments: Some technology options can affect multiple resources, e.g. nuclear power could reduce GHG emissions and reduce the exposure to volatile fossil fuel markets. Although it would use water for cooling, nuclear power can generate electricity for seawater desalination. As with policies, a CLEW tool should allow a more inclusive assessment of technological options.
- Scenario development: Another goal is to elaborate consistent scenarios of possible socio-economic development trajectories with the purpose of identifying future development opportunities as well as understanding the implications of different policies. This is important for understanding whether current development is sustainable, and for exploring possible alternative development scenarios and the kinds of technology improvements that might significantly change development trajectories.

VI-6. Developing a CLEW system analysis framework

This section provides an initial outline of a CLEW system. It provides only an indication of substantive interactions in the CLEW system, which are represented in simplified aggregate reference system diagrams (RSDs). This initial attempt is meant to provoke future quantitative investigations, and many aspects are therefore deliberately aggregated.

VI-6.1. Energy

An aggregate simplified RSD featuring the energy segment of a CLEW tool is shown in Fig. VI-1. Figures VI-2–VI-4 will focus on the water, climate and land use segments.

Primary energy (on the left of Fig. VI-1) is needed to provide energy services (on the right of the figure), such as lighting, cooking, heating and

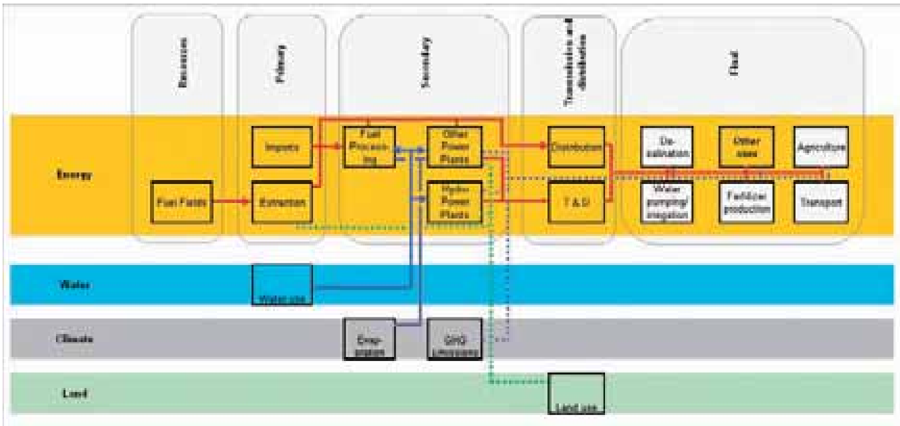

FIG. VI-1. Aggregate reference system diagram: energy.

motive power. Primary energy is extracted from renewable or depletable resources[45]. Extraction, whether from wind farms or mines, scars and requires land[46]. Biofuel production requires water[47] and cultivable land[48], thereby reducing their availability for other activities. Often biomass collected for fuel wood in poor regions with growing populations contributes to deforestation and land degradation.

After energy is extracted, it is processed into forms which are easier to use or transport. For hydropower, electricity is generated from run of river turbines or water stored in reservoirs. This can require the use of large land areas and the significant alteration of water flows. Where vegetation is flooded, it will decompose and release GHGs such as methane. For other energy sources electricity and heat are the most common forms in which energy is transported or used. Crude oil, biofuel feedstocks, coal and natural gas can also be transformed into petroleum products and other liquid fuels.

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[45] Note that where a renewable resource such as fuel wood is consumed faster than it is regrown, it is also in a sense depletable, especially where land is damaged due to overuse.

[46] A 60 MW(e) solar thermal power plant, for example, requires about 1 square kilometre of land [VI-20], and more land might be required to provide back-up power to augment the intermittent nature of solar energy.

[47] The biofuel feedstock maize, for example, needs about 860 litres of water to produce one litre of ethanol.

[48] For example, over 3000 square kilometres of land can be required to produce 18 million tonnes of the biofuel, palm oil, annually [VI-21].

Generally, primary fuel extraction, fuel processing[49] and electricity generation require large amounts of cooling water[50]. The combustion of fossil fuels commonly releases GHGs such as CO_2.

Fuels are then transported, distributed and converted into the energy services mentioned earlier. Conversion devices range from the simple to the complex, for example from appliances (like a kettle) to equipment (like a compressor) to more complex technologies (like an automobile). Energy services are important in all socio-economic sectors. For integrated CLEW analyses, noteworthy energy services include the transportation of biofuels and crops, pumping of water for irrigation, and energy consuming chemical processes for manufacturing fertilizer. In most cases, GHGs and various pollutants are emitted either directly if non-renewable fuels are burned, or indirectly if they are burned to produce the fuel that is used to produce the energy service.

VI-7. Water

An aggregate simplified RSD featuring the water segment of a CLEW tool is shown in Fig. VI-2.

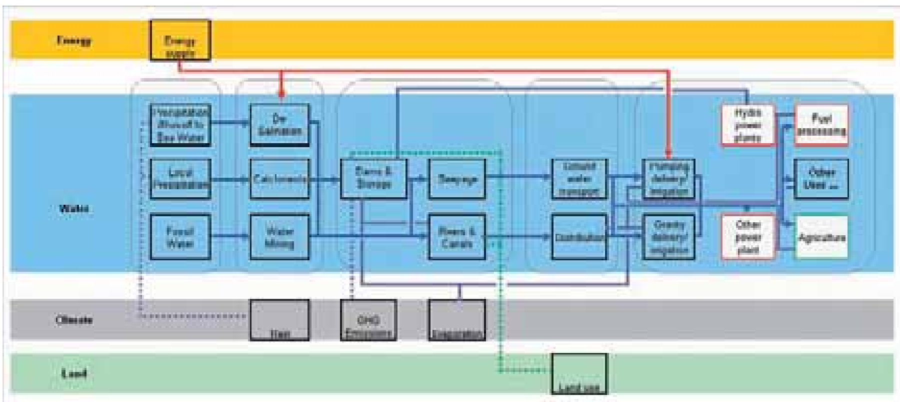

FIG. VI-2. Aggregate reference system diagram: water.

[49] According to the United States Bureau of Land Management, surface mining and retort operations produce 8–38 litres of wastewater per tonne of processed oil shale [VI-22]. Similarly, an estimated three barrels of water are required per barrel of oil equivalent of tar sands.

[50] In the face of water shortages in dry areas, special technologies have been developed to reduce water use by about 60% in steam cycle thermal power plants [VI-23].

Water, like energy, provides a number of essential services. Broadly speaking, there are three water sources: the sea, local precipitation and aquifers (or 'fossil water'). Seawater can be desalinated using energy for evaporation or reverse osmosis. Local precipitation fills river basins and lakes with fresh water, and fossil water can be mined. Where water supplies are far from demand, water is pumped or fed to users via canals or pipes and can be stored in reservoirs. When aquifers are depleted faster than they are replenished, their levels will drop, and more pumping (and therefore fuel) may be required to supply the same amount of water. Such pumping can be an extensive user of energy[51].

In the power sector, thermal power plants[52] use large amounts of water for cooling — much of which is lost to evaporation. Hydropower plants use significant quantities of land[53] and interfere with existing water flows, changing silting patterns in river basins[54]. Significant quantities of water are also required for other energy processing activities, such as refining oil products or manufacturing synthetic fuels[55]. However, new 'dry cooling' technologies offer reduced water consumption in many activities which use water for cooling.

Water has a particularly important role to play in agriculture. In arid developing countries, irrigation can account for as much as 90% of total water use [24], and irrigation together with sufficient nutrients can transform marginal land to cultivable land (although overfertilization and irrigation can also damage land). Irrigation can be gravity driven but increasingly requires energy for pumping.

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[51] In California, for example, up to 3.5 kW·h per 1000 litres can be consumed supplying water. More energy can be required for local irrigation and treatment [VI-25].

[52] The US Geological Survey [VI-26] estimates that over 50% of freshwater withdrawals are for cooling thermal power plants, with the majority of that water returned to rivers, lakes or the ocean after use.

[53] The large land requirements of hydropower can require the relocation of activities and people. Over a million people, for example, had to be relocated because of the Three Gorges Dam Project [VI-27].

[54] Damming the Nile River, for example, caused the silt which was deposited in the yearly floods and made the Nile floodplain fertile to be deposited behind the dam. This lowered the water storage capacity of Lake Nasser. Poor irrigation practices further waterlog soils and bring the silt to the surface.

[55] In New Mexico, for example, refineries currently use 50–180 litres of water per barrel of crude oil and generate 30–120 litres of wastewater [VI-28].

After use, water has a high potential for purification and recycling, which, however, require energy[56].

As available water can be scarce, its management to reduce evaporation can be important. Thus low evaporation storage, drip irrigation, recycling, 'grey' water use, and other techniques and technologies are important in improving the efficiency of the water system.

Finally, water is returned to the atmosphere via evaporation and transpiration, with the greatest quantities released by evaporation from the ocean.

VI-8. Climate and weather

An aggregate simplified RSD featuring the climate segment of a CLEW tool is shown in Figure VI-3.

The climate is affected by releases of GHGs from anthropogenic activities[57] such as fossil fuel power production, fertilizer production and use, crude oil and biomass refining, transport and land cultivation [VI-29]. Fossil fuel combustion accounts for the bulk of emissions[58].

There is a significant drive to adopt energy technologies which mitigate or reduce the quantities of CO_2 emitted. Examples include nuclear energy and renewable energy such as hydropower, wind power and biofuels (such as diesel or ethanol produced from crops). Other methods of reducing CO_2 emissions include sequestering CO_2 in forests and the future use of CO_2 capture and storage technologies.

With changes in the climate come changes in weather patterns. When droughts occur, water for electricity generation is limited, irrigation demands increase and desertification can take place. Conversely flooding can damage crop land, infrastructure and human settlements.

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[56] For example, the energy required in California to treat wastewater for reuse ranges between 0.1 and 4.0 kW·h per 1000 litres [VI-25].

[57] Important contributors to anthropogenic releases include burning fossil fuels, land use, land use change, forestry, cement production, waste water processing, natural gas flaring and chemical processes and products [VI-30].

[58] The IPCC estimates that CO_2 from energy use accounted for 56% of global GHG emissions in 2004. Power generation accounted for 30.5% of total CO_2 emissions and transport for 17% [VI-31].

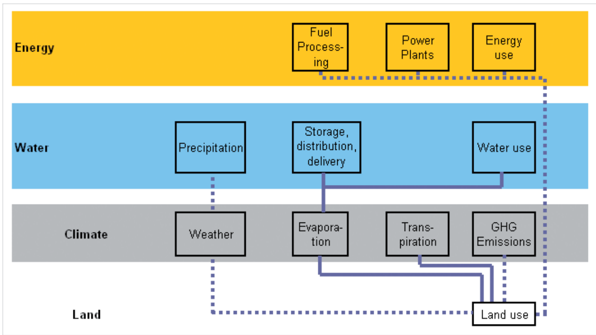

FIG. VI-3. Aggregate reference system diagram: climate.

VI-9. Land

An aggregate simplified RSD featuring the land segment of a CLEW tool is shown in Fig. VI-4.

Land that has the potential for cultivation can be classified into four categories: deserts, marginal land, cultivable land and forests or other natural vegetation such as savannahs. The quantity of cultivable land increases as either forests are cleared or marginal lands and deserts are made cultivatable by irrigation and fertilization.

The quantity of available land is limited. Thus, depending on the value of what it can produce, competition among alternative uses can be high. Typical land uses include habitation (such as in towns and cities), grazing of livestock, crops for food, biofuel and other products, fuel wood and infrastructure such as roads, cities, canals and dams. Where practices are poor, land can be damaged

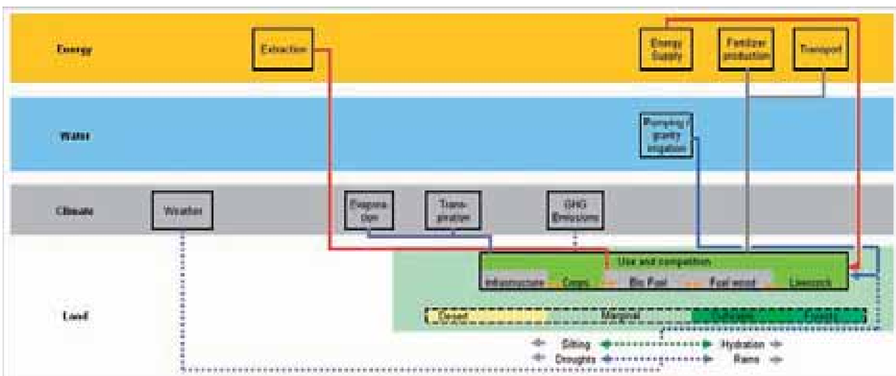

FIG. VI-4. Aggregate reference system diagram: land.

by overgrazing, overcropping and fuel wood harvesting. As vegetation changes, e.g. as dense forests, which contain substantial carbon in wood, are cleared for crops, significant amounts of carbon can be released to the atmosphere. Land can also be damaged through excessive silting and erosion related to agriculture and weather patterns. Depending on the crop, annual rainfall and quality and type of soil, different amounts of irrigation, fertilizer and land are required, with the production of each of these inputs having important impacts in turn, for example increased energy use and associated emissions.

VI-10. Towards a CLEW system representation

Figure VI-5 combines Figs VI-1–VI-4. The result is an initial simplified single CLEW reference system diagram (RSD).

The RSD is a useful tool for visualizing relations which need to be represented by simplified mathematical expressions. Each line represents a ‘flow’ and each box an activity, or group of activities, that change various flows. This approach is common, particularly in energy modelling where the RSD is known as a reference energy system (RES).

Once the flows, activities and their linkages are defined, the levels of each flow need to be calibrated in terms of physical quantities, and the activities

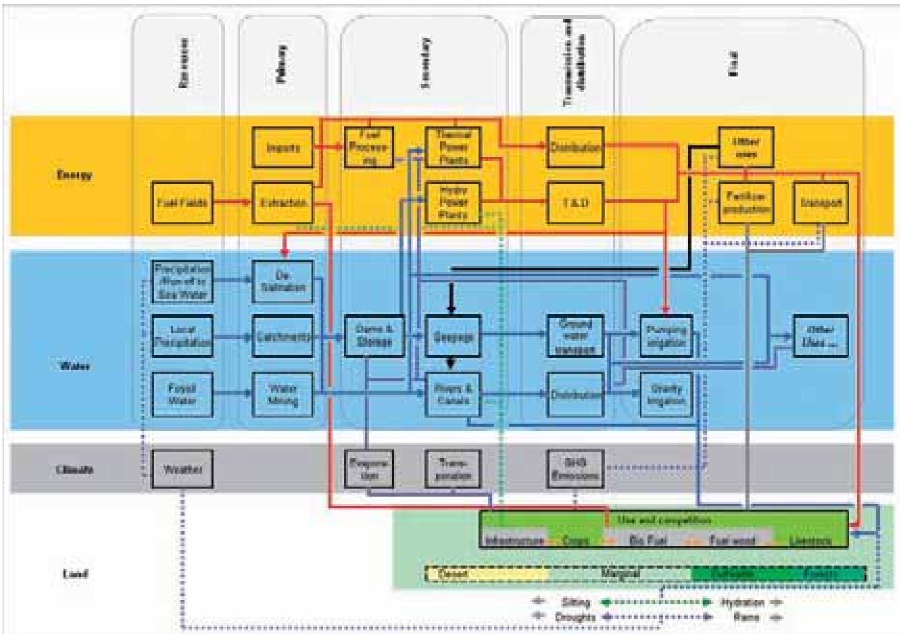

FIG. VI-5. Aggregate CLEW reference system diagram.

need to be calibrated in terms of their historical capacities (where systems of equipment are used), operational costs, investment costs, and technical characteristics (such as their efficiencies). Each system should meet a range of demands for services as an economy, or population, grows. However, flows and activities may be limited by physical or financial limits, and there may be restricted interactions between the demands for services and the manner in which they are provided. For example, a computer can be run only on electricity, not coal. Taken together and further developed, the set of relationships in a CLEW reference system can be implemented in a software tool and used to determine scenarios of how future needs can be met within the constraints inherent in the system.

This discussion provides only an outline of selected features of a CLEW tool. The final section addresses possible next steps and the unique role that the IAEA could play, within the family of UN organizations, in the development and application of such a tool.

VI-11. IAEA services

The UN has a broad mandate to help its Member States develop sustainably. It has adopted the Millennium Development Goals (MDGs) in the short term with the objective of meeting these goals by 2015. The commitment to sustainable development, however, reaches far beyond the MDGs. As an organization within the framework of the UN, the IAEA has a unique capacity to further contribute to these aims and support Member States and other agencies once a CLEW tool is available. The MDGs, and sustained longer term development, require services which all draw on the CLEW system either directly or indirectly. Without efficient policy design informed by a CLEW tool, development may be retarded.

The IAEA has a specific mandate to efficiently meet the needs of its Member Sates. The concerns of developing Member States include the provision of clean water, energy security and food security. Through its own mandate to promote the peaceful use of nuclear technologies and techniques, the IAEA currently supports many projects on energy planning, nuclear desalination modelling, isotope hydrology and, through a joint Division with FAO, crop improvement. These services are provided to Member States through the IAEA's technical cooperation programme. The initial incubation of, eventual application of and training on a CLEW tool would form a very natural extension of these services.

Further, it is envisaged that after initial incubation of the concept within the IAEA, consultation with other experts and agencies in the UN system will take place.

VI-12. Conclusion

A tool to assess the interrelated aspects of climate, land, energy and water (CLEW) is definitely needed. This is essential in the context of sustainable development, the key challenge for the coming decades. Moreover, in order to meet growing demands for energy, water and food services, the CLEW system needs to be managed. Although the components of the CLEW system are closely interrelated, decision and policy making for each component usually take place separately. This can result in suboptimal resource allocations, counter-productive policies and, at worst, accelerating long term unsustainable development. Particular attention needs to be given to apparently short term gains which undermine longer term development opportunities.

A CLEW system would be a valuable addition to the IAEA suite of energy analysis and planning tools, especially for comparative technology and policy assessments, policy harmonization and designing and testing future scenarios of development. The IAEA provides an ideal setting to incubate a pre-prototype of a CLEW modelling tool. This tool could contribute to stimulating integrated CLEW analysis and planning in Member States and to supporting the achievement of broad UN development goals, and it could provide a natural and useful extension of current IAEA technical cooperation activities.

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