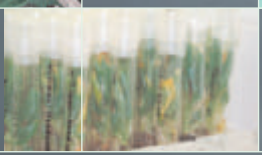
NUCLEAR TECHNOLOGY REVIEW

2004



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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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NUCLEAR TECHNOLOGY REVIEW
2004

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A. FUNDAMENTALS OF NUCLEAR DEVELOPMENT

A.1. Nuclear, Atomic and Molecular Data

The viability and credibility of a wide range of nuclear-based technologies require ready access to high-quality atomic, molecular and nuclear data. The Agency has a central role in establishing and maintaining extensive databases to encompass bibliographic information, theoretical and experimental data, and recording evaluated atomic and nuclear data. International links continue to be forged and maintained in order to ensure the needs and integrity of various programmes, for example advice and recommendations on atomic and molecular data are provided by the Atomic and Molecular (A+M) Subcommittee of the International Fusion Research Council, while similar guidance on nuclear data is given by the International Nuclear Data Committee.

The demands of new nuclear technologies continue to determine the direction(s) of future data development, including the requirements for data that address innovative fuel cycles, accelerator-driven systems, nuclear incineration, fusion devices, diagnostic and therapeutic medical treatment by radiation, optimization of medical isotope production, non-destructive materials testing, radiation analytical techniques (e.g. neutron activation analysis and ion beam analysis), minerals exploration and land-mine detection.

Some recent data development projects with diverse applications are a search engine for A+M data to permit simultaneous data retrieval from a number of different sources for both numerical and bibliographic databases to aid designers; the facility to make A+M theoretical calculations on-line, permitting the user to generate new data from theoretical models by running the appropriate codes at the sites of the institutes that maintain the codes; a data library on radiated power and ionization balance for plasmas of interest in fusion research, and a data library on standard reaction cross sections that will reduce the uncertainties of relative cross-section measurements, and thus contribute significantly to planned improvements in the new ional libraries.

A.2. Research Reactors, Accelerators and Radioisotopes

For over 50 years, research reactors have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training. They remain core experimental instruments. As of June 2004, 672 research

reactors are recorded in the IAEA's Research Reactor Data Base (RRDB), of which 274 are operational in 56 countries (85 in 39 developing countries), 214 are shut down, 168 have been decommissioned and 16 are planned or under construction.

Many of those that are shut down, but not decommissioned, still have fuel, both fresh and spent, at the sites. An extended delay between final shutdown and decommissioning will affect both cost and safety at the time of decommissioning, mainly due to the loss of experienced staff (already ageing at the time of shut down) necessary to participate in decommissioning activities[1].

Under-utilization of research reactors is an issue of concern in many Member States. However, many research reactors in operation are extensively used at both national and international level for radioisotope production, beam line research, industrial applications, neutron irradiation and specialized applications. In addition, new multi-purpose and single-purpose research reactors are being built.

Use of highly enriched uranium (HEU) fuel is considered a potential proliferation threat. To date, 31 research reactors have undergone full conversion to low enriched uranium (LEU). Seven other research reactors have been partially converted, while others are awaiting conversion. The unavailability of a qualified high-density fuel, suitable for converting some specific research reactors, is an important concern. The problem of using LEU instead of HEU as target material in isotope production for medical applications is being given serious consideration.

Charged particle accelerators are powerful tools for a multitude of applications, such as probes for analysis of physical, chemical and biological samples; ion beam modification of surfaces and materials for enhancing desired properties; radioisotope production; radiation processing of materials and radiotherapy of cancer. The demand for synchrotron radiation and high-quality pulsed neutron beams from spallation sources used for materials research is increasing.

A variety of radioisotopes (more than 150 in different forms), predominantly of reactor origin, are in extensive use. Radionuclides suitable for radiotherapy and easily producible in research reactors, such as ^{177}Lu are being intensively evaluated for development of radiopharmaceuticals. Also, small sealed sources of ^{125}I and ^{103}Pd are being researched for treatment of eye and prostate tumours. Positron emission tomography (PET) tracers from medical cyclotrons, F-18 fluorodeoxyglucose (FDG) in particular, are making an increasing impact, mainly in oncology.

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[1] Annex I refers.

B. POWER APPLICATIONS

B.1. Nuclear Power Today[2]

"The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformations of these atoms is talking moonshine." Lord Ernest Rutherford, 1933.

"It is not too much to expect that our children will enjoy in their homes [nuclear generated] electrical energy too cheap to meter." Lewis Strauss, Chairman, US Atomic Energy Commission, 1954.

Half a century on, we know the truth lies somewhere between the extremes[3].

Nuclear power supplied 16% of global electricity generation in 2002, and as of 31 December 2003 there were 439 NPPs operating worldwide (see Table B-1). Their global energy availability factor has risen steadily from 74.2% in 1991 to approximately 84% in 2003. In 2003 two new NPPs were connected to the grid, a 665 MW(e) pressurized heavy water reactor (PHWR) in China and a 960 MW(e) pressurized water reactor (PWR) in the Republic of Korea. In addition Canada restarted two units that had been shutdown. Construction started on one new NPP in India. Four 50 MW(e) units in the UK were retired, as were one 640 MW(e) unit in Germany and one 148 MW(e) unit in Japan.

Current expansion and growth prospects are centred in Asia. Eighteen of the 31 reactors under construction[4] at the end of 2003 are located in China, India, Japan, the Republic of Korea and the Democratic People's Republic of Korea. Twenty-one of the last 30 reactors to have been connected to the grid are in the Far East and South Asia.

In Western Europe, capacity is likely to remain relatively constant despite nuclear phase-outs in Belgium (which passed its phase-out law in January 2003), Germany and Sweden. The most advanced planning for new nuclear capacity is in Finland. In 2003 the utility Teollisuuden Voima Oy selected Olkiluoto as the site for a fifth Finnish reactor and signed a contract with a Framatome ANP – Siemens consortium for a 1600 MW(e) European pressurized water reactor. The construction licence application for the reactor was submitted to the Finnish Government in January 2003.

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[2] Annex II refers.

[3] Annex III refers.

[4] The total includes also Taiwan, China.

TABLE B-1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2003)

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2003		Total Operating Experience to Dec. 2003	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	7.03	8.59	50	7
ARMENIA	1	376			1.82	35.48	36	3
BELGIUM	7	5 760			44.61	55.46	191	7
BRAZIL	2	1 901			13.34	3.65	25	3
BULGARIA	4	2 722			16.04	37.71	129	2
CANADA	16	11 323			70.29	12.53	486	11
CHINA	8	5 977	3	2 610	41.59	2.18	39	1
CZECH REPUBLIC	6	3 548			25.87	31.09	74	10
FINLAND	4	2 656			21.82	27.32	99	4
FRANCE	59	63 363			420.70	77.68	1 346	2
GERMANY	18	20 643			157.44	28.10	648	0
HUNGARY	4	1 755			11.01	32.69	74	2
INDIA	14	2 550	8	3 622	16.37	3.30	223	5
IRAN, ISLAMIC REPUBLIC OF			2	2 111			0	0
JAPAN	53	44 139	3	3 696	230.80	25.01	1 123	7
KOREA, DEM. PEOPLE'S REP. OF			1	1 040			0	0
KOREA, REPUBLIC OF	19	15 850	1	960	123.28	40.01	220	8
LITHUANIA	2	2 370			14.30	79.89	36	6
MEXICO	2	1 310			10.51	5.23	23	11
NETHERLANDS	1	449			3.80	4.48	59	0
PAKISTAN	2	425			1.81	2.37	35	10

TABLE B-1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2003)

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2003		Total Operating Experience to Dec. 2003	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ROMANIA	1	655	1	655	4.54	9.33	7	6
RUSSIAN FEDERATION	30	20 793	3	2 825	138.39	16.54	761	4
SLOVAKIA	6	2 442	2	776	17.86	57.35	100	6
SLOVENIA	1	656			4.96	40.45	22	3
SOUTH AFRICA	2	1 800			12.66	6.05	38	3
SPAIN	9	7 584			59.36	23.64	219	2
SWEDEN	11	9 451			65.50	49.62	311	1
SWITZERLAND	5	3 220			25.93	39.73	143	10
UKRAINE	13	11 207	4	3 800	76.70	45.93	279	10
UNITED KINGDOM	27	12 052			85.31	23.70	1 329	8
UNITED STATES OF AMERICA	104	98 298			763.74	19.86	2 871	8
Total	439	361 094	31	25 387	2524.03		11 143	5

Note: The total includes the following data in Taiwan, China:

— 6 units, 4884 MW(e) in operation; 2 units, 2600 MW(e) under construction;

— 37.37 TW·h of nuclear electricity generation, representing 21.5% of the total electricity generated in 2003;

— 134 years and one month of total operating experience.

In the Russian Federation, ROSENERGOATOM continued its programme to extend licences at eleven NPPs. In 2003, the Russian nuclear regulatory body, Gosatomnadzor, issued a five-year extension for Kola-1. Bulgarian regulators issued a new ten-year licence for Kozloduy-4, the first long term licence in Bulgaria, and later issued a similar eight-year extension for Kozloduy-3. Romania, where licence extensions are required every two years, approved an extension for Cernavoda to 2005.

In 2003, the US Nuclear Regulatory Commission (NRC) approved nine licence extensions of 20 years each (for a total licensed life of 60 years for each NPP), bringing the total number of approved licence extensions to nineteen by the end of the year. It also approved eight upratings totalling 401 MW(th). Three companies applied for the NRC's new early site permits, which can be reserved for future use. In Canada, near-term expansion is taking the form of restarting some or all of the eight nuclear units (out of a Canadian total of 22) that have been shut in recent years. The first two such restarts, Pickering A-4 and Bruce A-4, took place in 2003. Meanwhile, licences have been extended for four units to 2005, and for eight units until 2008.

The key issues affecting near term nuclear expansion are economics, safety and security, waste and proliferation resistance.

Economics: The front-loaded cost structure of NPPs means that existing amortized well-run plants can be quite profitable while new NPPs are often more expensive than alternatives. But economic attractiveness differs for different countries, investors and markets. New NPPs are most attractive where energy demand growth is rapid, alternative resources are scarce, energy supply security is a priority or nuclear power is important for reducing air pollution and GHG emissions. NPPs are also more attractive to government investors responsible for energy security, GHG emissions, and long-term development than for private investors who need rapid returns and receive no financial benefit from nuclear power's low GHG emissions or contribution to energy security. Thus in deregulated, slower growth markets in the West, new NPPs are generally less attractive. Anticipating entry-into-force of the Kyoto Protocol, Europe is creating a GHG emissions market, and future investors may thus realize a tangible benefit from nuclear power's low GHG emissions. The USA is exploring alternative ways to adjust near term market incentives to encourage nuclear expansion in line with the longer term US National Energy Policy.

Safety and Security: Although the Chernobyl accident still hangs over nuclear power, the industry's current safety record has considerably improved. World Association of Nuclear Operators statistics for 2003 show a low stable rate of unplanned automatic scrams at about one third the level at the beginning of the 1990s, and a continuing decrease in the already low industrial

accident rate. However the challenges continue to be to ensure that nuclear facilities worldwide are operated according to the highest levels of safety, to improve the 'succession planning' for the nuclear industry, to ensure that lessons learned in one country are effectively and thoroughly communicated to all countries, and that these lessons are incorporated into the operational and regulatory practices of all relevant nuclear facilities. More detailed safety information and recent developments related to all nuclear applications are presented in the Agency's annual *Nuclear Safety Review*.

Actions regarding potential threats of nuclear and radiological terrorism have taken on new urgency. Around the world, nuclear plants have strengthened security forces, added barriers, and taken other protective measures to address new perceptions of security risks. The Agency has greatly expanded the scope and volume of its nuclear security activities. It is important to understand how safety and security aspects relate to each other in the identification and protection of vulnerabilities in nuclear installations. The Agency has increasingly been asked to provide guidance on how to reconcile the need for transparency, in matters of nuclear and radiation safety, with the need for confidentiality, from a security perspective. Effective risk management will involve striking a balance that protects the security of sensitive information while ensuring that safety concerns continue to be corrected in a transparent manner, and that lessons learned, relating to both safety and security, are shared for the benefit of the entire nuclear community.

Spent fuel and waste: As shown in Figure B-1 inventories of spent fuel (SF) are growing due to limited reprocessing and delays in disposal. For high level waste, the most progress on disposal facilities has been made in Finland, Sweden and the USA. Finland's Government and Parliament have approved a

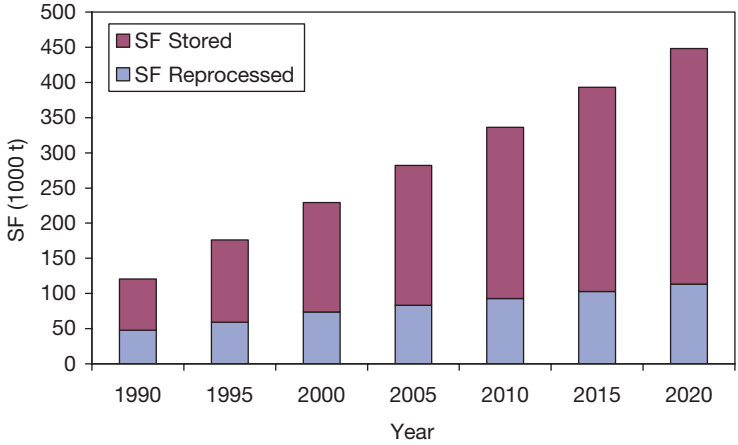

FIG. B-1. Cumulative worldwide spent fuel reprocessing and storage, 1990–2020.

decision 'in principle' to build a final repository for spent fuel near Olkiluoto. Separate construction and operating licences will also be required. Construction should start in 2011 and operation in 2020. Sweden has begun detailed geological investigations at two candidate sites. These should run for five or six years, and the Swedish nuclear fuel and waste management company, SKB, hopes to make a final site proposal by about 2007. The Waste Isolation Pilot Plant in the USA began accepting military transuranic waste in 1999 for permanent disposal in bedded salt. In 2002, the US President and Congress decided to proceed with the Yucca Mountain disposal site, operations at which are planned to begin in 2010. Although the present focus remains on establishing national repositories, there is renewed interest in the possibility of regional or international repositories. One reason is the interest noted below in increasing international control of nuclear material as one effort to strengthen the global non-proliferation regime. The other is the reality that for countries with no good waste sites, or with small research and power programmes, individual national disposal sites make no economic sense.

Proliferation resistance: Proliferation resistance is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, in order to acquire nuclear weapons or other nuclear explosive devices. The degree of proliferation resistance results from a combination of, inter alia, technical design features, operational modalities, institutional arrangements and safeguards measures. Most recently, in particular in the context of ongoing work for innovative reactors and fuel cycles, increased attention is being paid to the issue of *intrinsic* proliferation resistance features, i.e. those features that result from the technical design of nuclear energy systems, as well as to *extrinsic* proliferation resistance measures, i.e. those measures that result from States' decisions and undertakings related to nuclear energy systems. The ongoing work on new reactor types and fuel cycles includes in all cases considerations about such proliferation resistance features and measures that help ensure that future nuclear energy systems will continue to be an unattractive means to acquire materials for a nuclear weapons programme.

B.2. The Future

B.2.1. Medium term projections

Each year the Agency publishes updated medium term nuclear energy projections, and in 2003 these were extended for the first time to 2030 (see Table B-2). The low projection essentially assumes no new NPPs beyond what

TABLE B-2. ESTIMATES OF TOTAL ELECTRICITY GENERATION AND CONTRIBUTION BY NUCLEAR POWER

Country Group		2002			2010			2020			2030		
		Total Elect. TW·h	Nuclear		Total Elect. TW·h	Nuclear		Total Elect. TW·h	Nuclear		Total Elect. TW·h	Nuclear	
			TW·h	%		TW·h	%		TW·h	%		TW·h	%
North America		4779	851.1	17.8	5034	874	17	5784	870	15	6451	844	13
					5444	894	16	6709	939	14	8146	944	12
Latin America		1078	28.6	2.7	1178	29	2.5	1628	47	2.9	2227	30	1.3
					1427	38	2.7	2291	50	2.2	3758	92	2.4
Western Europe		3084	880.2	28.5	3352	858	26	3634	823	23	3942	564	14
					3609	893	25	4687	961	20	6061	1090	18
Eastern Europe		1758	298.5	17	1884	319	17	2174	423	19	2463	378	15
					2074	399	19	2867	552	19	4133	611	15
Africa		459	12	2.6	538	13	2.5	699	14	2	876	14	1.6
					612	14	2.3	973	24	2.4	1530	60	3.9
Middle East and South Asia		1176	19.6	1.7	1342	41	3.1	1805	53	3	2327	70	3
					1626	47	2.9	2596	100	3.9	3946	194	4.9
South East Asia and the Pacific		600			736			934			1162		
					786			1119	5.5	0.5	1584	18	1.2
Far East		3157	484.3	15.3	3399	695	20	4199	855	20	5073	981	19
					4296	702	16	6605	1125	17	9830	1361	14
World Total	Low Estimate	16090	2574.2	16	17463	2830	16	20857	3085	15	24520	2881	12
	High Estimate				19873	2987	15	27848	3756	13	38989	4369	11

is already being built or firmly planned today, plus the retirement of old NPPs. The projection was revised upward in 2003 and projects a 20% increase in global nuclear generation up until the end of 2020 (compared to a 2% projected increase last year), followed by a decrease, resulting in global nuclear generation in 2030 only 12% higher than in 2002. Nuclear power's share of global electricity generation decreases after 2010 to 12% in 2030, compared to 16% in 2002. Increases are most substantial in the Far East, and decreases are greatest in Western Europe.

In the high projection, global nuclear generation steadily increases by a total of 46% through 2020 (unchanged from last year's high projection) and by 70% through 2030. There are increases in all regions, again led by the Far East. However, overall electricity generation increases even faster than nuclear power, causing nuclear power's share of overall electricity to decline. By 2030 the nuclear share is down to 11%.

B.2.2. Sustainable development and climate change

For the longer term, the key question is how long nuclear resources might last. Known conventional resources are sufficient for a number of decades at current usage rates as shown in Table B-3, although the period for which resources are sufficient decreases the more nuclear power is assumed to grow in the future. As is also shown in the table, undiscovered conventional resources increase the period for which resources are sufficient to several hundred years if the necessary (and substantial) exploration and development investments are made. *Unconventional* resources, including phosphate deposits and seawater, contain vast amounts of very dilute uranium, and their use could fuel nuclear energy for millennia if advanced extraction methods are developed. Currently, only laboratory-scale quantities have been extracted from seawater, and the projected cost is approximately five to ten times the cost of conventionally mined uranium. Significant effort and investment would be needed before these resources could become available.

Thorium is three times as abundant in the earth's crust as uranium. Natural thorium is essentially 100% thorium-232, which is not fissile. It is however fertile, absorbing slow neutrons to become fissile thorium-233. Thus a future thorium-based fuel cycle to generate electricity from this resource could significantly extend the lifetime of global nuclear resources.

Nuclear energy, as well as renewables, could meet a larger share of the world's growing energy needs through the development of hydrogen fuel cell vehicles and other hydrogen applications. Hydrogen can be produced from water using electricity, the principal product of nuclear energy and of renewable technologies like wind power. An economical conversion process,

TABLE B-3. YEARS OF RESOURCE AVAILABILITY FOR VARIOUS NUCLEAR TECHNOLOGIES[5]

Reactor/Fuel cycle	Years of 2002 world nuclear electricity generation with known conventional resources (1)	Years of 2002 world nuclear electricity generation with total conventional resources (2)	Years of 2002 world nuclear electricity generation with total resources (3)
Current fuel cycle (LWR, once-through)	85	270	8 200
Recycling fuel cycle (plutonium only, one recycle)	100	300	9 200
Light water and fast reactors (mixed with recycling)	130	410	12 000
Pure fast reactor fuel cycle with recycling	2 500	8 500	240 000

(1) Known conventional resources include all cost categories of reasonably assured resources (RAR) and estimated additional resources – category I (EAR-I) for a total of 4 588 700 tU.[6]
(2) Total conventional resources include all cost categories of reasonably assured resources, estimated additional resources, and speculative resources for a total of 14 382 500 tU.
(3) Total resources assume conventional resources of 14 382 500 tU, plus 90% of phosphate resources of 22 000 000 tU (= 19 800 000 tU), plus 10 % of the estimated seawater uranium resources of 4 000 000 000 tU (= 400 000 000 tU) for a total of 434 182 500 tU.

coupled with economical hydrogen distribution and end-use technologies, would make it possible for nuclear energy and renewables to help fuel the transport sector, which is now 95% fuelled by oil, and expand nuclear power's

[5] OECD Nuclear Energy Agency and International Atomic Energy Agency, *Uranium 2003: Resources, Production and Demand*, OECD, Paris, 2004.

[6] Full definitions of RAR and EAR-I are given in *Uranium 2003 : Resources, Production and Demand*. Briefly, RAR refers to uranium occurring in known mineral deposits and recoverable with current technology. EAR-I refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence.

contribution to industrial heat supplies. There are new major hydrogen research initiatives underway, particularly in China, Europe, Japan and the USA. All these initiatives also include innovative nuclear designs that would produce hydrogen more directly without first having to generate electricity.

No progress was made in 2003 on the Kyoto Protocol, which would help make nuclear power's avoidance of GHG emissions valuable to private investors. Following the World Summit on Sustainable Development (WSSD) in 2002, major deliberations on energy and sustainable development are not scheduled until the thirteenth session of the UN Commission on Sustainable Development (CSD) in 2006–2007. The WSSD had endorsed earlier CSD decisions on nuclear energy. These are that countries agree to disagree about whether nuclear power is an important contributor to sustainable development, while they all agree that the choice rests with individual countries.

B.2.3. Advanced fission and fusion[7]

In response to the challenges currently facing nuclear power as outlined in Section B.1, many countries are working to improve the economics, safety and proliferation resistance of advanced reactor–fuel cycle systems. For advanced NPP designs, efforts are focussed on making plants simpler to operate, inspect, maintain and repair. In the near term, most new NPPs are likely to be evolutionary designs building on proven systems while incorporating technological advances and often economies of scale. For the longer term, the focus is on innovative designs, several of which are in the small-to-medium range (up to 700 MW(e)). These envision construction with factory-built components, including complete modular units for fast on-site installation, creating possible economies of series production instead of economies of scale. Other advantages foreseen for smaller units are easier financing, greater suitability for small electricity grids or remote locations, and their potential for district heating, seawater desalination and other non-electric applications. All should increase their attractiveness for developing countries.

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

[7] Annex IV refers.

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

Complementing the many initiatives above are two major international efforts to promote innovation — GIF and the Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). Members of GIF are Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the UK, the USA and Euratom. GIF has reviewed a wide range of innovative concepts and, in 2002, selected six types of reactor systems for future bilateral and multilateral cooperation: gas cooled fast reactors, lead alloy liquid metal cooled reactors, molten salt reactors, sodium liquid metal cooled reactors, supercritical water cooled reactors and very high temperature gas reactors.

Members of the Agency's INPRO project are Argentina, Brazil, Bulgaria, Canada, China, France, Germany, India, Indonesia, the Republic of Korea, the Netherlands, Pakistan, the Russian Federation, Spain, South Africa, Switzerland, Turkey and the European Commission. INPRO published an initial report in 2003 that outlined the potential of nuclear power and specified guidelines and a methodology for evaluating innovative concepts. It is now validating that methodology through test applications in a series of case studies.

Much of the current experimental and theoretical research on nuclear fusion is focused on the International Thermonuclear Experimental Reactor (ITER). ITER's 'engineering design activities' stage has been completed, and the project is nearing a decision on site selection. In 2003, it gained three new members, with China, the Republic of Korea and the USA (which had originally left ITER in 1999) now joining the EU, Japan and the Russian Federation. The two proposed sites are in France and Japan.

Research also continues on other magnetic confinement approaches, and inertial confinement is being developed intensively by national programmes in France and the USA. The National Ignition Facility in the USA is scheduled for completion in 2008.

C. APPLICATIONS FOR FOOD, WATER AND HEALTH

C.1. Nuclear Techniques in Crop Improvement

Nuclear techniques have played, and continue to play, a significant role in crop improvement. Applications are varied, but major areas of impact are: germplasm enhancement in crop plants through induced mutation; development of genetic markers for genetic fingerprinting, genetic mapping and diagnostics through several techniques including radiolabeling of DNA markers; and gene discovery through targeted mutagenesis.

Induced mutations, created by gamma rays, X-rays, fast neutrons or chemicals, have provided some major successes in plant breeding. In many cases new phenotypes, such as the semi-dwarfs in rice and barley, revolutionized the appearance of the crop. Mutant varieties of oil seeds and pulses are now being released for commercial cultivation. More subtle changes, but equally important, have been created for disease and pest resistance, nutritional and processing quality. Beneficial mutants have been captured and exploited by plant breeders: 2316 officially registered mutant varieties are listed in over 160 plant species worldwide (FAO/IAEA Mutant Variety Database).

The improvement of screening methods has led to resurgence in applications of radiation-induced mutations. For example salt tolerant rice mutants have been obtained by gamma-irradiation at Seibersdorf. Selection was made easy by a rapid hydroponics test in which 2000 seedlings were screened. Four mutants were selected and salt tolerance verified in the field. The mutant lines show no adverse characters and rice breeders of the International Rice Research Institute are actively breeding with them. The target area for salt tolerant rice cultivars in Asia is estimated at 618 000 ha.

The explosion in DNA sequence information has led to a shift in genetic studies from structural to functional. Gene function is now a major objective in genetics. Mutants are a key element in this research as they provide a rapid screen for the systematic discovery and functional analysis of genes. TILLING (Targeting Induced Local Lesions In Genomes) is one such technique, a reverse genetics technique in which large mutant populations can be systematically screened using DNA sequence data.

C.2. Nuclear Techniques in Crop Protection

In recent years, the Sterile Insect Technique (SIT) has become a more cost-effective technology for fruit fly suppression, capable of competing in cost with conventional insecticide-based suppression.

One of the most relevant improvements has been the development of genetic sexing strains (GSS) such as the male-only medfly temperature sensitive lethal (*tsl)* strains, which have reduced by half transportation and release costs and have increased the effectiveness of the sterile males in the field at least by three fold. The use of male-only strains is now the norm for medfly SIT and countries that have acquired medfly rearing capacity have now incorporated the GSS into their mass production processes.

It has been estimated that the potential demand for sterile medflies in the Mediterranean basin alone amounts to at least 4 billion sterile males per week, close to the total number currently being produced worldwide. Continuous improvements and new scientific developments augur a promising future for SIT for a number of species of economic importance such as false codling moth, codling moth, date moth, bollworms and various other pest insects, including sweet potato weevils. Also development of genetic sexing strains for other key insect pests to enhance the cost-effectiveness of SIT technology will continue to be a focus of research and development.

C.3. Improving Livestock Productivity and Health

Screwworm eradication using SIT from all of North and Central America at an overall cost of ca. $1 billion, is estimated to provide annual benefits to the livestock industry in this region that exceed the overall investment in the eradication campaign of over 45 years. However, in Africa tsetse fly transmitted trypanosomosis makes the introduction of productive mixed farming and livestock systems impossible. Overall losses due to trypanosomosis in the agricultural gross domestic products of tsetse-infested countries in Sub-Saharan Africa are estimated at $4.75 billion per year.

Internationally agreed priority areas for agricultural development have been identified, where tsetse and trypanosomosis intervention, including the SIT component, would likely generate quick, tangible and sustainable benefits in the context of agricultural development and ecologically appropriate utilization of resources. Internationally concerted action in these priority areas is most advanced in the Ethiopian Southern Rift Valley, where preliminary cost-benefit analyses predict a break-even point of benefits over investments made after 5–6 years and an internal rate of return over a 12-year period

between 33% and 43%. The Arab Organization for Agricultural Development, the FAO and the Agency continue to collaborate in a joint regional feasibility project against the Old World screwworm fly in the West Asia region.

Research aimed at improving animal production and health in the developed world has been revolutionized by recent developments in biotechnology, in particular those related to gene-based technologies. These developments enable new and innovative approaches to find unique solutions to both emerging and old problems.

In animal production, the characterization of livestock genomes will enable the identification of advantageous genes, such as those responsible for natural resistance to diseases or the ability to thrive under climatic or nutritional stress. Hybridization and related techniques that employ ^{32}P and other isotopic markers together with non-isotopic molecular tools for identification of genes, microsatellites and quantitative trait loci will allow the selection and breeding of resistant animals, thus enhancing or replacing conventional methods of disease control.

Notwithstanding developments, the more 'mature' nuclear technologies such as radioimmunoassay (RIA), employing ^{125}I to measure hormones and metabolites in the blood or milk of animals, continue to be widely used. RIA for the hormone progesterone is an indispensable tool that provides information both on problems in breeding management by farmers as well as deficiencies in the artificial breeding services provided to them by government, co-operative or private organizations. RIA is also a cheap and robust method for the detection of harmful residues in food of animal origin, such as those arising from the misuse of veterinary drugs.

Molecular diagnostics have entered an exciting era in animal health, increasing the sensitivity and specificity of tests to detect animal diseases. An important goal of many diagnostic devices is the ability to perform point-of-care testing to ensure speedy and accurate pathogen detection. Improvements in instrumentation and its availability will enable technologies such as '$^{35}S/^{32}P$ phospho-imaging gene sequencing' to be implemented in developing countries. Developments in microfabrication technology, microfluidics and nanotechnology are promising to produce more sensitive, rapid and robust devices that have the ability to perform under diverse conditions. Lab-on-a-chip devices offer the ability to integrate sample processing, target amplification and detection in a single miniaturized device. Leading on from such technologies will be the development of diagnostic kits based on biochips capable of detecting multiple infective agents (i.e. antigen) or presence of pathogen (i.e. antibody) in a single, highly sensitive, specific and fast assay. Their adaptation for field use will clearly revolutionize the diagnosis,

prevention and control of devastating livestock diseases in developing countries[8].

C.4. Food Safety

Currently 70 irradiation facilities are in use in over 33 countries worldwide for ensuring the safety and quality of foods and for satisfying quarantine regulations in trade, including meat products, fresh fruits, spices and dried vegetable seasonings.

The 26th Session of the Codex Alimentarius Commission (Rome, Italy, 30 June – 7 July 2003) adopted the *Revised Codex General Standard for Irradiated Foods* and the Codex *Recommended International Code of Practice for Radiation Processing of Food* as final Codex texts. In addition, the 5th Session of the Interim Commission on Phytosanitary Measures (ICPM) (Rome, Italy, 7-11 April 2003), the governing body of the International Plant Protection Convention (IPPC), adopted *Guidelines for the Use of Irradiation as a Phytosanitary Measure*. Both the Codex and the IPPC standards have legal status under the WTO/SPS Agreement.

There will be an increasing need for nuclear techniques to ensure the safety and quality of foods and to validate and standardize low cost analytical methods for food contaminants and residues suitable for developing countries. Co-ordinated efforts in these areas will strengthen food security and ensure the facilitation of international trade in foodstuffs through an integrated approach covering the entire food chain.

C.5. Towards Sustainable Land and Water Management

The WSSD in Johannesburg, September 2002, re-affirmed land degradation as one of the major global environment and sustainable development challenges of the 21st century. The Agency has focused attention on the use of radionuclide tracers, in particular ^{137}Cs, to obtain quantitative estimates of soil erosion and deposition on agricultural landscapes, which will provide retrospective information on medium-term (30–40 years) erosion and deposition rates and spatial patterns of soil redistribution, without the need for long term monitoring programmes. Currently over 40 research groups have the capacity to conduct these investigations.

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[8] Annex V refers.

The FAO/IAEA programme is actively involved in further research and development on combined use of ^{137}Cs with other environmental radionuclides, such as ^{210}Pb and ^{7}Be to assess both erosion and sedimentation rates and patterns at several spatial and temporal scales. Such information will be valuable in the identification of promising soil conservation measures for controlling and mitigating soil erosion and sedimentation and development of strategies for sustainable watershed management and environmental protection.

The World Water Forum held in March 2003 in Kyoto, Japan, recognized the challenge of the urgent need to effectively increase both the Crop Water Productivity and Water Use Efficiency of the agricultural sector. Research into using nuclear techniques to develop practical tools and guidelines for the enhancement of water productivity under various management and climatic conditions and selection of plants efficient for drought prone environments is being pursued. The carbon isotope discrimination technique has shown potential as a valuable tool for identifying drought tolerant genotypes.

C.6. Water Resources

Improved understanding of the earth's water cycle has been widely recognized as one of the key elements of scientific information necessary for developing policies toward a sustainable management of freshwater resources. The applications of isotopes in hydrology, arising from naturally imparted 'isotopic fingerprints' of water, helps to provide rapid hydrological information for large areas at low cost.

Twelve isotope or isotope pairs are commonly used in isotope hydrology, with stable isotopes of oxygen and hydrogen being the most frequently used. Tritium and helium-3 are increasingly being used for age-dating of young groundwater, reflecting the dominant role of groundwater in meeting freshwater demands worldwide.

Isotope techniques are routinely used for groundwater resource evaluations by the US Geological Survey (USGS) where most of the regional aquifer system analysis programmes have employed isotope techniques for estimating groundwater recharge. Similar examples of the use of isotopes in groundwater management are found in Australia, France, Germany, India, United Kingdom, and a number of other countries. Recently, the application of isotopes for managing surface water resource and to improve the understanding of climate change on water resources has been advanced by a comprehensive study of the isotopic compositions of most major rivers in the USA. More than seventeen research groups participating in an Agency co-ordinated

research project are now designing a global network of isotope monitoring in large rivers.

Isotopic composition of precipitation collected through the national and global networks of monitoring stations has provided a new dimension for Atmospheric Global Circulation Models (AGCMs) that are used for reconstructing paleoclimatic conditions in support of global change research. Institutions in France, Germany, and the United States of America have recently expanded the use of global isotope data of precipitation to better represent and verify the simulation of hydrological processes in AGCMs. Models based on isotope data have improved process understanding and are considered to more reliably simulate past climatic conditions.

Over 250 participants from 69 countries recently discussed the past, present and future of isotope applications in hydrology and climate research at a symposium convened by the Agency in 2003. The symposium concluded that isotope applications will continue to be important for groundwater resource management and are likely to be critical in efforts to understand and predict climatic and atmospheric processes. This important role for isotopes in understanding past climate change also holds the key to predicting future changes — changes that may not only influence global temperatures, but also energy needs, availability of drinking water, and food security.

C.7. Human Health

C.7.1. Nutrition

Some conventional methods used to evaluate health and nutritional status can be invasive, inaccurate, insensitive to small variations, and not easily transferred to the field. The alternative nuclear and isotope techniques are increasingly regarded as essential tools in applied nutrition and research. Isotopic technology has been effective to build programmes and guidelines aimed at reducing many forms of malnutrition. Some of the main techniques are isotopic dilution technique for body composition analysis; double labelled water technique for energy metabolism; trace mineral bioavailability using stable isotopes; vitamin A body storage determination; dual X-ray-absorptiometry measurements for bone mineral density; and ^{13}C breath test for tracking infection.

C.7.2. Nuclear medicine

Diagnostic applications

Nuclear medicine imaging and non-imaging functional studies offer diagnostic and research applications of internally administered open sources of radioactivity. There is also an increase of therapeutic applications. These techniques are used in several specialties such as cardiology, oncology, nephrology, neurology, infections and genetics.

Nuclear medicine imaging and non-imaging functional studies: Gamma Camera and SPECT (single photon emission computed tomography) are used routinely in clinical medicine providing both static and dynamic information leading to diagnosis and prognosis of diseases, determination of organ function and valuable information about treatment response. Positron emission tomography (PET) has emerged as a powerful tool to diagnose disease earlier, determine its extent and response to treatment, estimate residual disease after treatment, predict prognosis and understand bio-molecular behaviour. PET is making rapid strides in the developed countries but complexity and cost restrict its routine clinical use in most developing countries.

The use of gamma probes for the detection and biopsy of the sentinel lymph node has revolutionized patient management in surgical oncology and changed the concept of managing malignant melanomas and breast and colon cancers.

Molecular nuclear medicine techniques: Molecular methods have applications in rapid disease screening and diagnosis, pathogenesis, guiding therapeutic decisions, monitoring and management, epidemiological investigations, immunology, pharmacogenomics and molecular designing of new drugs and vaccines. A key element involving these techniques is the amplification of pathogen specific gene sequence by polymerase chain reaction, which is used to detect mutations responsible for drug resistance in malaria and tuberculosis, as well as sub typing of HIV and designing vaccines against it.

Radiopharmacology and radioimmunotechnology: Radiopharmacology deals with tracer kinetics and development and evaluation of various radiopharmaceuticals. The introduction of new tracers and innovative applications may have a significant impact on health care services such as oncology, cardiology and infections.

Medical radioimmunoassay and immunotechnology constitute a significant component of the in vitro diagnostic system for quantification of changes in proteins as well as other important intermediate metabolites in disease states especially in developing countries. They are also being used in developmental work to explore novel methods for patent applications, and as reference standards for verification of non-isotopic assays.

Therapy

High-dose rate brachytherapy: In recent years, high-dose rate (HDR) brachytherapy has become a very important component of the treatment of uterine cervix cancer. In contrast to low-dose rate brachytherapy equipment that had been traditionally employed but could only treat 2–3 patients each week, HDR allows dozens of patients to be treated each day along with unprecedented possibilities for radiation dose optimization.

Profiling of genes and proteins: Genomic and proteomic revolutions in biology and medicine mean that large-scale microarrays have recently become available that can analyse several thousand genes or proteins in a short period of time. This technology holds great promise for pre-selecting future patients and/or cancers with regard to their response to radiation.

Stem-cell therapeutics: Radiotherapy has long been utilized as a part of the preparatory regimen for bone-marrow transplantation. Recent research suggests that radiotherapy, in conjunction with cellular or stem cell transplantation, could also play a valuable role in the regeneration of other organs as well, such as the liver, pancreas and the central nervous system.

Dosimetry and medical radiation physics

The proper measurement of ionizing radiation (dosimetry) is crucial to enable the safe and effective use of nuclear technology for diagnosis and treatment of patients. Over 250 participants from 62 countries discussed issues in dosimetry at a recent symposium convened by the Agency in Vienna. More than 90 recommendations were prepared to guide future work highlighting the needs: for more training of health care workers in the provision of infrastructural services; for appropriate and affordable equipment to sustain diagnostic and treatment technologies; and for the development of physical standards, comparisons and audits of quality assurance and control programmes to demonstrate the safe and effective application of nuclear technology to patients.

D. APPLICATIONS FOR ENVIRONMENTAL AND SUSTAINABLE INDUSTRIAL PROCESSES

D.1. Protection of the Marine and Terrestrial Environments

D.1.1. Marine environment

The protection of the marine environment and management of ocean resources are particularly complex and difficult. Of key importance is the protection of the socio-economically important coastal zones, near where 40% of the world's population lives and which produce the major portion of the world's seafood.

Among the most important problems facing the coastal environment have been public health and safety issues, ecosystem health, eutrophication (over-fertilization leading to oxygen deprivation), harmful blooms and other hazards such as coastal flooding and sea level changes. The phenomenon of 'harmful algal blooms' (HABs) has had wide economic impacts on the fishing and seafood industries, and tourism. Nuclear techniques in the form of receptor binding assays have helped, as an analytical tool, to counter the growing incidence of HABs which need rapid, sensitive and inexpensive assays which are sensitive to low toxin concentrations.

Radioactive decay characteristics of certain natural radionuclides make them excellent geochronological tools for dating e.g. the time sequence of sediment layering in certain marine areas. Knowledge of the timing of sedimentation events helps to establish temporal trends of marine pollutants. A wide variety of radioisotopes as analogues for heavy metals, particularly the gamma-emitters, are useful tools to trace the transport, behaviour and fate of heavy metal contaminants in water, sediments and marine organisms under laboratory conditions.

D.1.2. Terrestrial environment

Prevention of the release of pollutants

Acidic pollutants such as sulphur and nitrogen oxides are emitted during fossil fuel combustion, leading to acidic rain and smog formation. Electron beams modify the sulphur and nitrogen oxides in the off-gases and allow them to react with added ammonia to produce clean effluents and fertilizer. The key advantage of the radiation treatment is that the toxic compounds are transformed into useful and harmless products. The electron beam flue gas

treatment plants are operating in coal-fired plants in China and Poland (in both cases purification of flue gases from 100 MW(e) blocks), with high efficiency of SO_x and NO_x removal. Nuclear technologies, involving electron beams, electromagnetic radiation or isotopic sources, have also been used for decontaminating and disinfecting aqueous effluents, sewage waters, industrial wastewaters and sludge by destroying harmful and toxic organic substances and micro-organisms. A combined technology, using an electron beam and ozone, has been developed for the removal of chlorinated hydrocarbons from drinking water. Another application permits the radiation sanitation of biological sludge from biological wastewater treatment, allowing the sludge eventually to be used as fertilizer.

Environmental monitoring and research

Nuclear techniques and measurement methods are also widely used for environmental monitoring and research using natural and artificial radionuclides as indicators for atmospheric, terrestrial and marine transport processes.

The advent of radionuclide methods in geochronology has revolutionized the understanding of modern sedimentary processes in aquatic systems. Methods based on ^{210}Pb and $^{87/86}Sr$ are used as quantitative tools in marine and lake sediment geochronology. In addition ^{137}Cs and other natural and anthropogenic radionuclides strongly absorbed at the soil surface, present at very low but still measurable concentrations, have been used to study soil erosion and soil deposition phenomena.

Humanitarian demining

Abandoned landmines from past and present armed conflicts continue to pose a threat to populations in more than 60 countries in the developing world. A typical anti-personnel landmine contains very little metal and is therefore difficult to detect by normal metal detection means. Very sensitive metal detectors can detect low-metal content landmines, but they cannot distinguish between mines and other small, buried metal objects, such as shrapnel fragments. A nuclear method based on interrogation by neutrons is one of the few methods that enable non-intrusive elemental analysis of buried objects, detecting the hydrogen content of the mine explosive. An instrument based on a pulsed electrostatic neutron generator (PELAN, Pulsed Elemental Analysis by Neutrons) for humanitarian demining has been the basis for much research and shows promise. Tests showed that the PELAN device could reliably identify anti-tank mines with 5–6 kg of TNT buried under 15 cm of soil and anti-personnel mines with 200g of TNT under 5 cm of soil. A definitive conclusion could not be reached in the case of detecting smaller anti-personnel mines, and detection limits still need to be improved. To achieve full success,

PELAN would have to be integrated with a suitable anomaly detection device, for example a metal detector or ground penetrating radar, for field applications. Also, hand held devices have been developed based on neutron backscattering for the detection of plastic landmines in dry areas. These instruments have been tested under field like conditions and it is foreseen that these types of devices will be used by the demining community, in combination with a metal detector, for the detection of plastic landmines.

D.2. Radiation Technology for Clean and Safe Industries[9]

A vast variety of nuclear techniques are available for industrial, environmental, medical or research applications. Radiation and isotopic technology such as gamma irradiation, electron beam or ion beam as well as nucleonic gauges, radiotracers and sealed sources, non-destructive testing and nuclear analytical techniques are used for process control, material modifications, to reduce harmful industrial emissions and to reprocess waste streams, and many other uses.

In addition to the economic impacts of radiation and radioisotope applications they produce major impacts on different aspects of social and industrial development, for example in human health (radiation sterilization of medical products, blood and transplanting grafts irradiation); environmental protection (electron beam flue gas and wastewater treatment, gamma rays sludge hygienization); clean and safe industry (radiotracer leakages testing and non destructive testing of installations, pipes and tanks); enhancement of product quality (nuclear analytical techniques, non-destructive testing); process optimization (radiotracers and nucleonic control systems); raw materials exploration and exploitation (on-line processing, borehole logging), and security (cargo inspections, governmental mail irradiation).

There are now more than 160 industrial gamma irradiators worldwide, 65 units being in developing countries. More than 20% of these gamma irradiators have activities over 1 MCi. The total number of accelerators worldwide exceeds 13 000. New environmental applications demand development of high power, reliable accelerators, and the most powerful radiation processing facility, over 1 MW total power, has been constructed for power plant emitted flue gases purification in Poland.

The relatively new field of nanotechnology uses electron beam technology for some applications, such as lithography. Nanometric structures

[9] Annex VI refers.

have already been tested, and other possible applications are concerned with conductive and multiphase polymers.

Radiotracers in industry and environment provide invaluable tools in many processes, for example in oil fields and refineries, chemical and metallurgical industries and wastewater purification installations. Common radioisotopes for tracers are ^{3}H, ^{82}Br, ^{99m}Tc, ^{140}La, ^{24}Na and ^{131}I.

D.2.1. Nuclear analytical techniques

Nuclear analytical techniques play an important role in certification of element content in a variety of materials, and are of particular value in international trade because legal limits have to be observed for food items and analytical results have to be based on mutual recognition, which is obtained if laboratories work according to internationally accepted quality standards such as the ISO 17025. New trends in nuclear applications can be seen in the development of robust, automated and portable instruments, which can be used under laboratory as well as under field conditions. Nuclear techniques also serve in preserving human cultural heritage. Neutron activation analysis is a very sensitive multi-elemental analysis for trace element fingerprinting to distinguish original specimens from fakes, and has been applied to coins and other metallic artefacts, stones, pottery and ceramics.

D.2.2. Nuclear desalination[10]

Interest in nuclear desalination is driven by the expanding global demand for fresh water and by developments in small and medium sized reactors that may be more suitable for desalination than large power reactors. In the field of nuclear desalination, Japan has accumulated over 125 reactor-years experience and Kazakhstan 26 reactor-years before shutting down the Aktau fast reactor in 1999. Egypt has completed a feasibility study of a nuclear co-generation plant (electricity and water) at the El-Dabaa site. France has completed a joint European study on reactor development for nuclear desalination (the EURODESAL project). India is setting up a 6300 m^3/d hybrid multi-stage flash (MSF)-reverse osmosis (RO) nuclear desalination demonstration plant at Kalpakkam. The RO plant is commissioned and the full plant commissioning is expected in 2004. Canada has completed the functional testing of a preheat reverse osmosis process and is considering a pre-commercialization demonstration programme. China has carried out a pre-feasibility study of the

[10] Annex VII refers.

Shandong nuclear seawater desalination plant in the Yantai area using an NHR-200, and Indonesia is conducting a preliminary economic feasibility study of nuclear desalination on Madura Island. The Republic of Korea completed the basic design of the SMART concept in 2002, and a six-year project for the construction of a one-fifth scale pilot plant SMART-P was started to verify the integral performance of the SMART system and nuclear desalination. Pakistan is continuing its efforts to set up a 4800 m^3/d nuclear desalination demonstration plant to be connected to a PHWR at KANUPP. In the Russian Federation, design work continues for a floating nuclear heat and power plant based on marine reactor technologies. Construction of the first plant is scheduled to begin in 2005 or 2006 in the northern European part of Russia. Plans call for a floating unit with two KLT-40S reactors to be used as the power source for nuclear desalination facilities. Tunisia is planning a pre-feasibility study of a customized nuclear desalination plant for specific site conditions.

E. SOCIO-ECONOMICS OF NUCLEAR ENERGY AND APPLICATIONS

Nuclear technology and techniques produce energy, make our food safer and more abundant, help prevent, diagnose, and cure disease, optimize sustainable water use, and protect the environment. Nuclear techniques have made significant contributions and have the potential to contribute much more in key areas of concern to the international community as identified by the World Summit on Sustainable Development in Johannesburg 2002 — water, energy, health, agriculture and biodiversity.

Their impact on future generations needs to be understood, because they affect a society's resources, institutions, public knowledge, human capital, manufactured capital and natural capital. In an increasingly globalized world, national or regional contributions may also benefit the global community and not just a single society. On the national and regional levels, nuclear sciences and applications are core disciplines on the road to a technologically advanced society. All countries take advantage of nuclear applications, especially in health care. While utilization increases dramatically with countries' social, technological, and economic development, significant socio-economic benefits can be obtained at all levels of development. To realize these benefits, radio-

logical contributions have to be properly embedded into major economic activities such as agriculture, health and energy[11].

Accurate assessments of their costs, benefits, and risks are needed, and continuing assessment is needed to ensure that the benefits of nuclear applications are available in those areas where it is worth utilising the atom. Major benefits have accrued and remain available to both developed and developing countries. Investments in the requisite technical, scientific, and regulatory infrastructure can be rewarded relatively quickly, even though some aspects may need many years to mature. The transfer by the Agency of human, regulatory, technical, and scientific nuclear capabilities are important activities for socio-economic development, but need to be put into context in terms of 'value added' or of comparative cost effectiveness with non-nuclear techniques. Assessment techniques need to be adapted to the relevant nuclear or isotopic application and studies need to define realistic boundary conditions for socio-economic impact assessments to be meaningful. The challenges of correctly assessing the impact of nuclear sciences and applications are large, but the results could provide clear justifications to decision makers on economic and social grounds for making choices regarding nuclear applications.

[11] Annex VIII refers.

ANNEX I: RESEARCH REACTORS

A. General Status

For over 50 years, research reactors (RR) have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training. As of June 2004, the Agency's Research Reactor Database contains information on 672 RR, of which 274 are operational in 56 countries (85 in 39 developing countries), 214 are shutdown, 168 have been decommissioned and 16 are planned or under construction.

It is of concern that many of the shutdown, but not decommissioned, reactors still have fuel, both fresh and spent, at the sites. An extended delay between final shutdown and decommissioning will affect both cost and safety at the time of decommissioning, mainly due to the loss of experienced staff (already ageing at the time of shutdown) necessary to participate in decommissioning activities.

The distribution of the number of countries with at least one RR peaked at 60 countries in the mid-eighties, coinciding with the peak at 41 for developing countries. The number of countries with at least one RR remained almost constant for industrialized countries from 1965 and for developing countries from 1985 to the present. Four industrialized countries and three

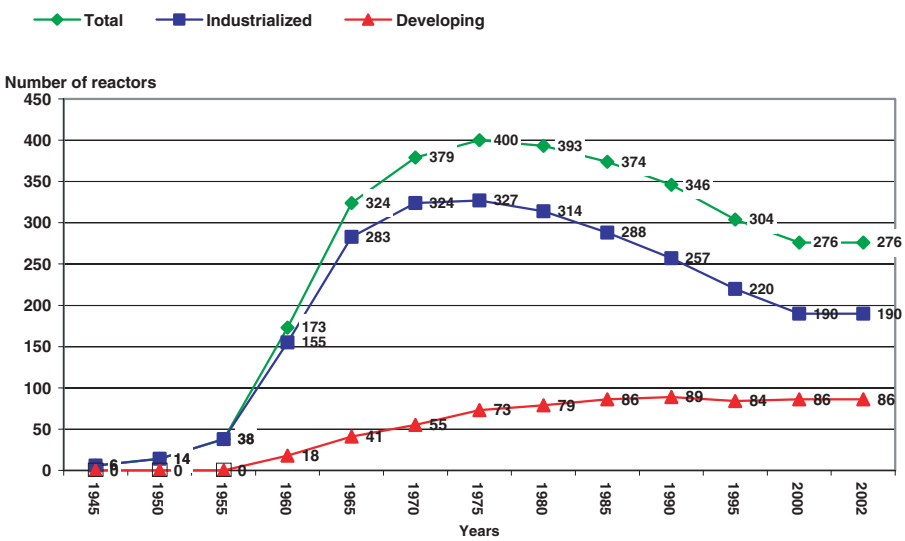

FIG. I.1. Number of research reactors in industrialized and developing countries.

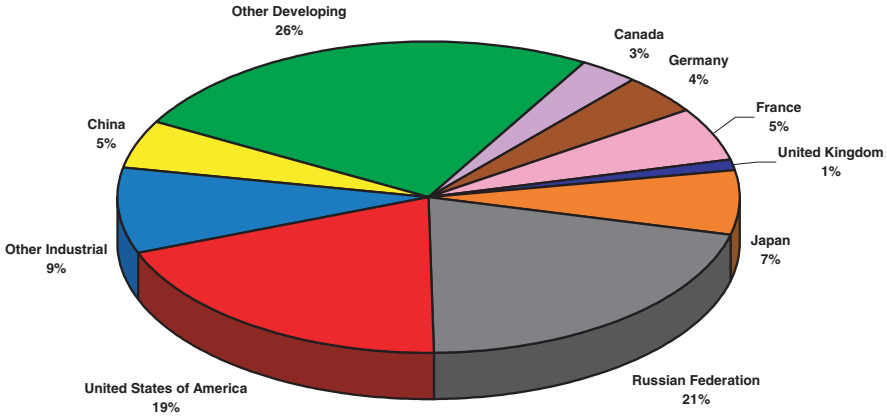

FIG. I.2. Operational research reactors in IAEA Member States – 273 reactors.

developing countries that once had operational RR no longer have any. Figure I.1 indicates that the number of RR in industrialized countries peaked in 1975 and has declined since then. The number in developing countries has gradually increased, but changed little since the mid-eighties.

Figure I.2 shows the distribution of operating research reactors among countries. About 70% are in the industrialized countries, with the Russian Federation and USA having the largest numbers.

Figure I.3 shows the decline in the number of new research reactors being brought into operation in the past four and a half decades, and the increase in the number being shutdown. The pattern reflects the nuclear field's evolution from a relatively new science into an established technology. It does not mean,

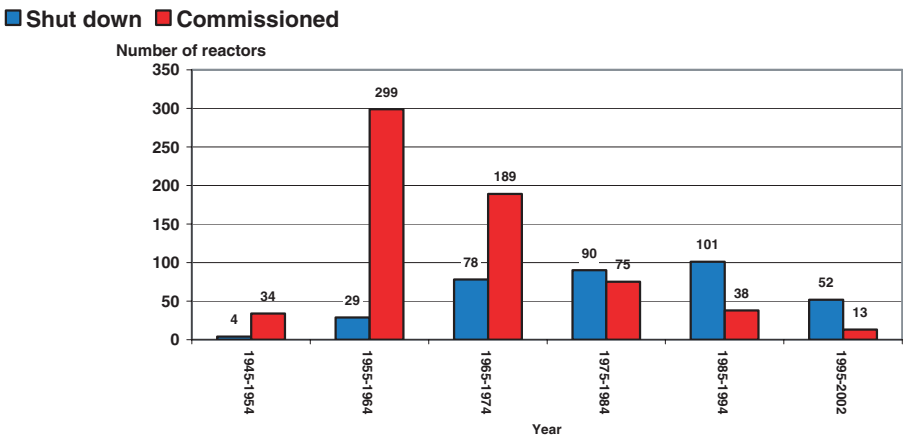

FIG. I.3. Number of research reactors commissioned and shutdown.

however, that new research reactors are unnecessary – eight are currently under construction and eight more are planned. For the most part these are innovative, multipurpose reactors designed to produce high neutron fluxes. Many will meet all the nuclear research and development needs envisioned in the countries in which they are being built, and will offer opportunities for visiting scientists from abroad. In addition, some will provide radioisotopes locally and regionally.

Figure I.4 shows the age distribution for operational research reactors. It peaks around 40 years, with almost 65% of operating reactors being more than 30 years old. While a few of these old reactors give cause for safety concerns, the majority have been refurbished at least once so that their key components meet modern safety and technology standards. Figure I.5 shows the power distribution of operating research reactors. The thermal power distribution of operating RR indicates that a large fraction of RR, 77%, are less than 5 MW, so that, even in the worst case accidental scenario, there will not be any significant consequences off site. Fifty percent of operational RR are less than 100 kW, consequently they operate with a lifetime core and so no spent fuel problems will arise until these reactors are shut down permanently. But many of them operate with highly enriched uranium fuel (HEU), i.e., a ^{235}U concentration ≥ 20%. HEU programmes are discussed in more detail in Section D of this annex, along with other special fuel cycle challenges associated with research reactors.

Research reactors present special challenges in the back end of the fuel cycle because many different designs using a large variety of fuel types have been built, often for special purposes. These include the management of experimental and exotic fuels with no reprocessing route, and significant numbers of

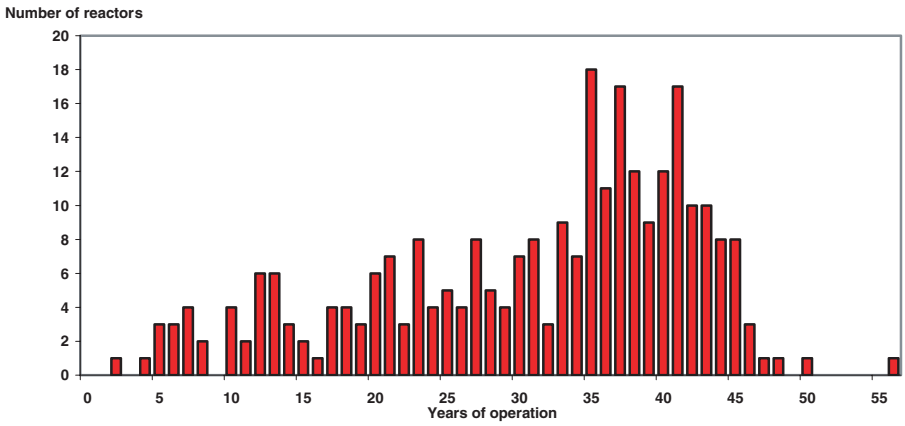

FIG. I.4. Age distribution of research reactors in the RRDB: Number of reactors and years in operation.

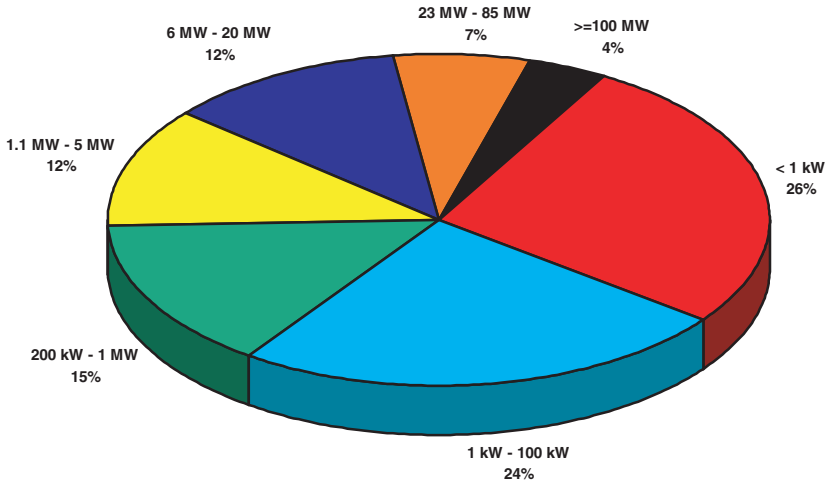

FIG. I.5. Pie chart showing distribution of thermal powers of operating reactors.

fuel assemblies that failed in their reactors or were subsequently corroded in wet storage. Similarly the variety of designs poses special challenges for decommissioning.

B. General Trends

The worldwide demand for nuclear science research, technology development, reactor services, and education and training no longer requires the large number of research reactors currently in operation. Reactors that prosper are those that have special attributes (e.g., a high neutron flux, a cold source, or in-core loops to simulate power reactor conditions) or have diversified to take advantage of commercial opportunities (e.g., radioisotope production or silicon doping). A much larger number are under-utilized. Older research reactors will therefore continue to be shut down in increasing numbers, and more of those that have already shut down will plan and implement decommissioning.

New reactors will be built, but in much smaller numbers than in the past, and will either be multipurpose reactors or dedicated to specific needs, for example, the new research reactor planned for Australia is multipurpose. The high flux multipurpose reactor, FRM II, currently being commissioned in Germany, will be used largely for research using neutron beams. The two Maple reactors being commissioned in Canada are based on a research reactor design but are essentially commercial isotope factories designed to produce ^{99}Mo by fission.

Currently, there are eight new research reactors under construction and plans for about eight more. As is usual in the case of research reactors, they vary significantly in power, type and purpose. There is one 30 kW Miniature Neutron Source Reactor (MNSR) that will be used primarily for education and training, plus some neutron activation analysis (NAA) related to national interests in assessing pollution, mineral resources and soil fertility. Two or three facilities will be 1-2 MW multipurpose reactors of the TRIGA type used for a wide gamut of applications including education and training, some limited isotope production, neutron radiography and neutron beam-based materials research. They may also be used for silicon doping and boron neutron capture therapy.

There are several 10-100 MW compact core reactors with D_2O reflectors either being planned or under construction. Their primary purpose will be to provide high flux beams for state-of-the-art materials analysis instruments, but they will also be suitable for most of the other standard applications listed above, including significant isotope production. Four or five of the new reactors will be dedicated to single purposes, such as isotope production, testing materials and components for power reactors or desalination. Finally, one or two research reactors under consideration would be intended as prototypes for advanced power reactor designs.

Of the research reactors currently operating, many will continue to prosper by finding niches to exploit – such as providing test loops simulating power reactor conditions, neutron activation analysis services, gem colouring, silicon doping, and isotope production – and by being flexible enough to exploit other opportunities as they arise. At the same time these facilities provide important training for the scientists and engineers who are essential for continued progress in nuclear research and development.

Many of the higher flux, high utilization research reactors have recently been significantly upgraded, usually to improve the neutron flux, particularly for beam research. In this context, the modifications have involved making the reactor core more compact, increasing the power, and changing reflectors, as well as upgrading or adding cold sources. Whenever beam fluxes are increased, there is naturally a tendency to also add new instruments such as Ultra-Small Angle Neutron Scattering instruments or Spin-Echo spectrometers. Other major modifications have been undertaken recently to enable or enhance boron neutron capture therapy. The pioneering facilities generally add fission converters to obtain a higher epithermal flux, while others modify thermal columns or beam tubes to enable them to perform capture therapy studies, either for research or treatment.

C. Utilization

The climate for research reactors has changed in recent years. The original mission of some facilities has been accomplished or become obsolete. In other cases, applications can now be done better or more cheaply using newer technology. Tight budgets and changing priorities have caused some governments to cut back baseline support. The stagnation or decline of nuclear power in many industrialized countries has reduced the demand for nuclear education and training, and simulators have taken over some of the training of nuclear power plant operators previously provided by research reactors.

TABLE I.1. FREQUENCY OF APPLICATIONS OF RESEARCH REACTORS

Application	**Number of reactors declaring involvement**
Neutron activation analysis	71
Teaching	68
Training	63
Materials or fuel tests	53
Isotope production	48
Neutron scattering research	34
Neutron radiography	32
Transmutation (Si or gems)	21
Geochronology	14
Neutron capture therapy	9
Other uses	47

Table I.1 provides a good indication of the relative frequency of each major application among research reactors. The table's final category, 'other uses', includes topics ranging from public tours to reactor physics studies, instrument calibration, positron sources, electrical power production and neutron depth profiling.

D. Nuclear Fuel Cycle

D.1. General Overview

D.1.1. Inventories

The Agency has circulated questionnaires for its Research Reactor Spent Fuel Database (RRSFDB), and responses indicate that there are 62 027 spent fuel assemblies in storage and another 24 338 assemblies in the standard cores. Of the 62 027 in storage, 45 108 are in industrialized countries and 16 919 are in developing countries; 21 732 are HEU and 40 295 are LEU (low enriched uranium). The majority use standard types of fuel plus aluminium cladding, although some TRIGA fuel elements have stainless steel cladding. The remaining non-standard fuel types in 59 facilities pose special problems both for their continued safe storage and for their eventual final disposition. Figure I.6 compares the numbers of US-origin and Russian-origin HEU and LEU spent fuel assemblies at foreign research reactors that might be involved in take-back programmes. Currently 12 850 spent fuel assemblies of US-origin, and 21 732 of Russian-origin, are located at foreign research reactors.

D.1.2. Storage Conditions

Wet storage is the most popular storage technology for storing research reactor spent fuel. However, successful storage of aluminium-clad fuel depends on very strict water quality control. Although aluminium clad research reactor fuel has been successfully stored in water for over 40 years without significant signs of corrosion, penetration of the fuel cladding by pitting corrosion has

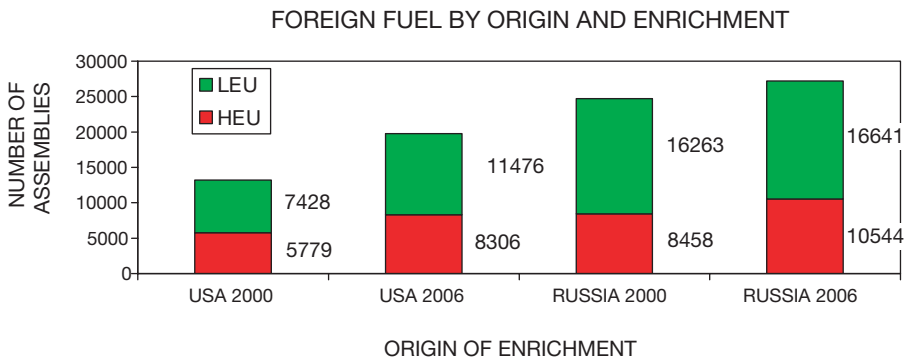

FIG. I.6. Present and projected US and Russian origin spent fuel at foreign research reactors potentially involved in take-back programmes.

occurred in as little as 45 days in cases where water quality has been allowed to deteriorate. Aluminium racks, tanks and pool liners used in storing aluminium clad fuel are equally vulnerable to corrosion and thus limit the life time of spent fuel storage facilities.

Research reactor fuel has also been successfully stored dry in vaults, concrete canisters and hot cells over long periods. Where problems have arisen, they have invariably been due to a long-term undetected ingress of water or moisture.

D.2. Reduced enrichment for research and test reactors (RERTR) and Fuel Return Programmes

D.2.1. RERTR

Section A noted that many research reactors operate on HEU fuel. To reduce and eventually eliminate commerce in HEU for research reactors, the United States set up the reduced enrichment for research and test reactors (RERTR) programme in 1978. A similar programme was initiated in the former Soviet Union, and these programmes have essentially merged with the Russian Federation becoming a full partner in RERTR. Thirty-one reactors to date have been fully converted to low enriched uranium (LEU has a ^{235}U concentration < 20%), and a further seven are in the process of converting with mixed HEU/LEU cores.

A major component of RERTR is the development and qualification of new, high-density, LEU fuels based on uranium molybdenum alloys. This effort has two goals: first, enabling further conversions of reactors from HEU to LEU and, second, developing a substitute for LEU silicide fuel that can be more easily disposed of after expiration of the United States Foreign Research Reactor (FRR) Spent Nuclear Fuel Acceptance (SNF) Program in May 2006 (see Section D.2.2).

The original schedule was to qualify LEU dispersion fuels based on U-Mo alloys with uranium densities of up to 6 g/cm^3 by the end of 2003, and those based on alloys with uranium densities of 8-9 g/cm^3 by the end of 2005. However, technical difficulties have been encountered that will delay qualification. These occurred during irradiation tests and were observed in the form of pillowing caused by excessive porosity in the (U-Mo)Al_x interaction product between U-Mo particles and the Al matrix under elevated operating conditions (i.e. a high temperature and fission rate). Planned irradiations to qualify full size fuel elements have therefore been postponed until a solution to this problem is developed, which will likely delay qualification until at least the end of 2010.

Promising results are being obtained in the effort to develop a fabrication process for monolithic LEU U-Mo fuel. Most existing and foreseen RR could be converted with this fuel, which has a maximum uranium density of between 15.4 and 16.4 g/cm^3. The most promising method produces the fuel meat by cold rolling a small ingot produced by casting. The aluminium clad and the fuel meat are then bonded by friction stir welding and the cladding surface is finished by a light cold-roll. This method has been demonstrated for mini-plates and appears to be possible for full size Materials Testing Reactor (MTR) plates, with the possible inclusion of intermediate anneals.

D.2.2. Fuel Return Programmes

The US Foreign Research Reactor (FRR) Spent Nuclear Fuel (SNF) Acceptance Program has made significant progress since its inception in May 1996. Under the programme, 4576 MTR elements have been received at the Savannah River Site and 961 TRIGA elements have been received at the Idaho National Engineering and Environmental Laboratory. These and projected future shipments are expected to greatly reduce the inventories of spent fuel at research reactors worldwide, thereby resolving operational problems at many reactor sites and reducing proliferation concerns.

The tripartite US-IAEA-RF Initiative on Russian Research Reactor Fuel Return to examine the feasibility of implementing a programme to return Russian origin research reactor fuel to the Russian Federation for management and disposition made steady progress during 2002. Agreements are in place and preparations are ongoing for the first shipment to take place from Tashkent, Uzbekistan.

Also under the auspices of the tripartite Initiative, an international operation involving Romania, the Russian Federation, USA and the Agency removed 14 kg of 80% enriched, and 36% enriched uranium from the Pitesti Institute of Nuclear Science in September 2003. The fresh fuel, originally obtained for the now shutdown WWR-S reactor at the 'Horia Hulubei' National Institute for Physics and Engineering in Magurele near Bucharest, was flown to Novosibirsk, Russia, where it is to be re-fabricated into LEU fuels. The Agency assisted Bulgarian authorities with the removal of HEU stored at the small (2 MW) IRT research reactor in Sofia. The HEU, 36% enriched and in the form of fresh fuel, was airlifted in December 2003 from Bulgaria to the Russian Federation, which agreed to take back the fuel which it had originally supplied.

Also within the framework of the tripartite US-IAEA-RF Initiative on Russian Research Reactor Fuel Return, the Agency assisted the Libyan authorities with the repatriation of 15 kg of 80%-enriched fresh HEU in

March 2004. The fresh HEU fuel was shipped to the Russian Federation, which agreed to its return.

E. Decommissioning

A breakdown of the statistical data used for Figure I.3 into shutdown and not yet decommissioned ('shutdown (NYD)') and decommissioned research reactors for individual regions and Member States yields a more precise picture of the importance of decommissioning issues. At present, close to 60% of the 'shutdown (NYD)' research reactors are located in North America with a further 12% in the Russian Federation. About 10% of 'shutdown (NYD)' research reactors are in developing Member States and distributed as follows: Asia-Pacific - 10; Eastern Europe - 8; Latin America - 4; and Africa and Middle East - 3.

However, as discussed in Section A, many of the operating research reactors in these regions are over 30 years old and a significant number will join the shutdown list in the next few years.

With respect to operational research reactors to be shut down and decommissioned in the future, a meaningful breakdown of the numbers is difficult, because future plans remain open for many countries.

ANNEX II: THE GLOBAL NUCLEAR POWER PICTURE

Worldwide there were 439 nuclear power plants (NPPs) operating as of 31 December 2003. Nuclear power supplied 16% of global electricity generation in 2002, down slightly from 16.2% in 2001.[12] Table II.1 summarizes world nuclear experience as of 31 December 2003.

The global energy availability factor for NPPs rose to approximately 84% in 2003, continuing its steady climb from 74.2% in 1991. Two new NPPs were connected to the grid in 2003. This follows six new connections in 2002 and three in 2001, specifically

2003: Qinshan 3-2 in China
Ulchin-5 in the Republic of Korea
2002: Ling Ao-1, Ling Ao-2, Qinshan 2-1, Qinshan 3-1 in China
Temelin-2 in the Czech Republic
Yonggwang-6 in the Republic of Korea
2001: Onagawa-3 in Japan
Yonggwang-5 in the Republic of Korea
Rostov-1 in the Russian Federation

There were six retirements in 2003, the four 50 MW(e) units at Calder Hall in the UK, the 640 MW(e) unit at Stade in Germany and the Fugen ATR 148 MW(e) unit in Japan. There had been four retirements in 2002 (Kozloduy-1 and -2 in Bulgaria and Bradwell units A and B in the UK) and no retirements in 2001.

In 2003, construction started on just one new NPP, a 202 MW(e) PHWR in India.

Current expansion, as well as near-term and long-term growth prospects, are centred in Asia. As shown in Table II.1, of 31 reactors under construction[13] worldwide at the end of 2003, 18 are located either in China, the Republic of Korea, the Democratic People's Republic of Korea, Japan or India. Twenty-one of the last 30 reactors to have been connected to the grid are in the Far East and South Asia.

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[12] International Atomic Energy Agency, Power Reactor Information System (PRIS) Database, (http://www.iaea.org/programmes/a2/); and International Atomic Energy Agency, *Reference Data Series No. 1*, Vienna, July 2003.

[13] The totals include also Taiwan, China.

TABLE II.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2003)

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2003		Total Operating Experience to Dec. 2003	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	7.03	8.59	50	7
ARMENIA	1	376			1.82	35.48	36	3
BELGIUM	7	5 760			44.61	55.46	191	7
BRAZIL	2	1 901			13.34	3.65	25	3
BULGARIA	4	2 722			16.04	37.71	129	2
CANADA	16	11 323			70.29	12.53	486	11
CHINA	8	5 977	3	2 610	41.59	2.18	39	1
CZECH REPUBLIC	6	3 548			25.87	31.09	74	10
FINLAND	4	2 656			21.82	27.32	99	4
FRANCE	59	63 363			420.70	77.68	1 346	2
GERMANY	18	20 643			157.44	28.10	648	0
HUNGARY	4	1 755			11.01	32.69	74	2
INDIA	14	2 550	8	3 622	16.37	3.30	223	5
IRAN, ISLAMIC REPUBLIC OF			2	2 111			0	0
JAPAN	53	44 139	3	3 696	230.80	25.01	1 123	7
KOREA, DEM. PEOPLE'S REP. OF			1	1 040			0	0
KOREA, REPUBLIC OF	19	15 850	1	960	123.28	40.01	220	8
LITHUANIA	2	2 370			14.30	79.89	36	6
MEXICO	2	1 310			10.51	5.23	23	11

TABLE II.1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 31 DECEMBER 2003) (CONT.)

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2003		Total Operating Experience to Dec. 2003	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
NETHERLANDS	1	449			3.80	4.48	59	0
PAKISTAN	2	425			1.81	2.37	35	10
ROMANIA	1	655	1	655	4.54	9.33	7	6
RUSSIAN FEDERATION	30	20 793	3	2 825	138.39	16.54	761	4
SLOVAKIA	6	2 442	2	776	17.86	57.35	100	6
SLOVENIA	1	656			4.96	40.45	22	3
SOUTH AFRICA	2	1 800			12.66	6.05	38	3
SPAIN	9	7 584			59.36	23.64	219	2
SWEDEN	11	9 451			65.50	49.62	311	1
SWITZERLAND	5	3 220			25.93	39.73	143	10
UKRAINE	13	11 207	4	3 800	76.70	45.93	279	10
UNITED KINGDOM	27	12 052			85.31	23.70	1 329	8
UNITED STATES OF AMERICA	104	98 298			763.74	19.86	2 871	8
Total	439	361 094	31	25 387	2524.03		11 143	5

Note: The total includes the following data in Taiwan, China:
— 6 units, 4884 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 37.37 TW·h of nuclear electricity generation, representing 21.5% of the total electricity generated in 2003;
— 134 years and one month of total operating experience.

Within Asia,[14] capacity and production are greatest in Japan (53 NPPs in operation and three under construction) and the Republic of Korea (19 NPPs in operation and one under construction). Both countries lack indigenous energy resources, and consequent concerns about supply diversity and security make new NPPs more economically competitive. In Japan, seven of the 17 reactors shut down in 2002 following revelations by the Tokyo Electric Power Company of past falsifications in self-imposed reactor inspection reports had been returned to service by the end of 2003. In China eight NPPs are in operation, and three more are under construction. India has 14 NPPs in operation, and eight under construction.

In Western Europe, with the retirement of four units in the UK and one in Germany, there are now 141 operating reactors. The last new connection to the grid was France's Civaux-2 in 1999. With upratings and licence extensions, overall capacity is likely to remain near existing levels, despite decisions to phase out nuclear power in Belgium (which passed its phase-out law in January 2003), Germany and Sweden. In contrast, voters in Switzerland rejected two referenda in 2003 proposing, in one case, an extended moratorium on new NPPs and, in the other, a nuclear phase-out. The UK Government decided it would not yet support the replacement of retiring nuclear plants with new nuclear capacity, preferring to promote renewables and turn to nuclear only if these prove insufficient. The most advanced planning for new nuclear capacity is in Finland where, in 2002, a 'decision in principle' to build a fifth NPP was made by the Government and Parliament. In 2003 the utility Teollisuuden Voima Oy selected Olkiluoto as the site and signed a contract with a Framatome ANP – Siemens consortium for a 1600 MW(e) European pressurized water reactor. The construction licence application for the reactor was submitted to the Finnish Government in January 2003.

Eastern Europe and the newly independent countries of the former Soviet Union have 68 operating NPPs and ten more under construction. In the Russian Federation, which has 30 NPPs in operation and three under construction, ROSENERGOATOM continued its programme to extend licences at eleven NPPs. In 2003 the Russian nuclear regulatory body, Gosatomnadzor, issued a five-year extension for Kola-1.

In Bulgaria a review by the World Association of Nuclear Operators concluded that Kozloduy-3 and -4 meet all necessary international standards to continue operating safely. Bulgaria has asked the EU to reconsider an earlier agreement under which Bulgaria would close Kozloduy-3 and -4 before the end of 2006 as a condition for joining the EU. In the meantime, Bulgarian

[14] Taiwan, China has six NPPs, with two more under construction.

regulators issued a new ten-year licence for Kozloduy 4 (through March 2013), the first long-term licence issued by Bulgaria, and later issued a similar eight-year extension for Kozloduy-3. In Romania, where licence extensions are required every two years, an extension was approved for Cernavoda to 2005.

No new NPP has been ordered in the United States of America since 1978, although seven units that were out of service for extended periods have been restarted since 1998. The focus in 2003 continued to be on licence renewal and upratings. In 2003, the US Nuclear Regulatory Commission (NRC) approved nine licence extensions of 20 years each (for a total licensed life of 60 years for each NPP), bringing the total number of approved licence extensions to nineteen by the end of the year. The NRC had 17 applications currently under review and expected at least eleven more in 2004, and eleven in 2005 and 2006. Also in 2003, the NRC approved eight upratings totaling 401 MW(th). As one step in implementing the 'Nuclear Power 2010' programme it announced in 2002, the US Government streamlined the regulatory process by introducing early site permits that can be reserved for future use. In the course of 2003 three companies, Exelon, Dominion Energy and Entergy Nuclear filed applications for such permits.

In Canada, near-term expansion of nuclear generation is taking the form of restarting some or all of the eight nuclear units (out of a Canadian total of 22) that have been shut in recent years. The first two such restarts, Pickering A-4 and Bruce A-4, took place in 2003. Meanwhile, licences for the four Pickering A units (three of which are still shut down) were extended to 2005, for the four Pickering B units (all operating) until 2008, and for the four Darlington units (all operating) until 2008.

In Africa, there are two operating NPPs, both in South Africa. In Latin America, there are six – two each in Argentina, Brazil and Mexico. In South Africa a further step forward was taken on the Pebble Bed Modular Reactor (PBMR) in 2003, with the issuance of a positive 'Record of Decision' on the environmental impact assessment study for the PBMR demonstration unit.

ANNEX III: 50 YEARS OF NUCLEAR ENERGY[15]

"The energy produced by breaking down the atom is a very poor kind of thing. Anyone who expects a source of power from the transformations of these atoms is talking moonshine." Lord Ernest Rutherford, 1933.

"It is not too much to expect that our children will enjoy in their homes [nuclear generated] electrical energy too cheap to meter." Lewis Strauss, Chairman, US Atomic Energy Commission, 1954.

In 2004, half a century after electricity produced by nuclear power was first delivered to an electrical grid at Obninsk in today's Russian Federation, we know the truth lies somewhere between the extremes.

Nuclear fission was discovered in 1939, and the world's first chain reaction was achieved by the Manhattan Project on 2 December 1942 at the University of Chicago. The Chicago nuclear pile consisted of uranium embedded in bricklike blocks of graphite to serve as the moderator. However, it was not until after the war, on 20 December 1951, that electricity was first generated from nuclear power. The source was EBR-I (Experimental Breeder Reactor-I), a fast breeder reactor at the National Reactor Testing Station in Idaho, USA. EBR-I initially produced about 100 kW(e), enough to power the equipment in the small reactor building.

A. International Developments

In the 1950s nuclear power research and development focused mainly on technologies for civilian electricity generation and naval propulsion, particularly submarines. The emphasis in the USA was on light water reactor (LWR) designs fueled with enriched uranium, both the pressurized water reactor (PWR) associated principally with Westinghouse and the boiling water reactor (BWR) associated with General Electric (GE). Development in the USSR covered both graphite moderated, light water cooled, enriched uranium designs and WWER designs (water cooled water moderated power reactor) similar to PWRs. British and French efforts focused on natural uranium fueled,

[15] This summary borrows heavily, frequently verbatim, from David Fischer's *History of the International Atomic Energy Agency: the first forty years*, IAEA, Vienna, Austria, 1997.

graphite moderated, gas cooled reactors (GCR).[16] Canada focused on natural uranium fueled, heavy water moderated designs.

Initial success, both for civilian power generation and submarine propulsion, came in 1954. On 9 May 1954 the 5 MW(e) graphite moderated, light water cooled, enriched uranium reactor at Obninsk, USSR reached criticality, and at 5:30 pm on 26 June 1954 it was connected to the Mosenergo grid. In December 1954, the first nuclear submarine, the Nautilus in the USA, began operation under nuclear power.

In 1956 Calder Hall-1, a 50 MW(e) GCR, came on line in the UK (and operated until March 2003). Shippingport in the USA was next, a 60 MW(e) PWR connected to the grid in 1957, followed in 1959 by G-2 (Marcoule) a 38 MW(e) GCR in France. Also in 1959, the world's first non-military nuclear powered ship, the icebreaker Lenin, was launched in the USSR. Figure III.1 presents a timeline showing these dates, the dates when nuclear power first came on line in other countries around the world, and, in the middle of the bar, the dates when total installed nuclear capacity worldwide reached 100 GW(e), 200 GW(e), and 300 GW(e). At the end of 2003, it stood at 361 GW(e).

An important contributor to the initial spread of nuclear power was a new post-war international openness and exchange, triggered most substantially by a United Nations conference in 1955 that came to be known as 'The First Geneva Conference'. It proved to be the world's largest gathering of scientists and engineers up to that time, and both confirmed for a broad audience that numerous uses of nuclear energy were now feasible, and lifted the blanket of secrecy that had covered nuclear research during the war.

European co-operation was also spurred by the Suez crisis in the Fall of 1956. At the height of the crisis, foreign ministers of the European Coal and Steel Community countries – France, the Federal Republic of Germany, Italy and the three Benelux countries – decided to appoint 'three wise men' to set targets for nuclear electricity. The target was 15 GW(e) of installed nuclear power by 1967, and in March 1957 the Rome treaties establishing both EURATOM and the European Economic Community were signed.

B. The 'Turnkey' Plants

By the early 1960s, demonstration power reactors were in operation in all leading industrial countries, and expectations were high. In December 1963,

[16] World Nuclear Association (http://www.world-nuclear.org/info/inf54.htm).

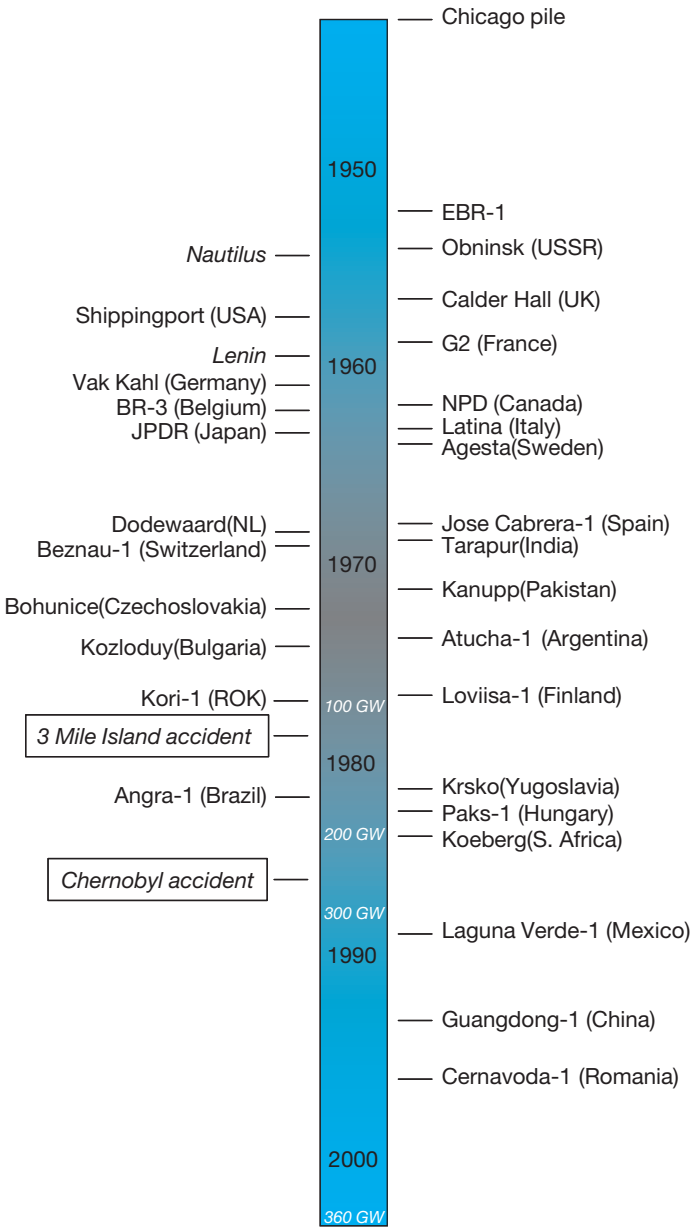

FIG. III.1. Timeline of first industrial scale NPPs around the world. The white numbers in the middle of the bar show when total installed nuclear capacity worldwide first passed 100 GW(e), 200 GW(e) and 300 GW(e).[17]

[17] Taiwan, China commissioned Chin Shan-1 in 1977.

the idea of 'turnkey' plants was introduced in the USA, with a bid for the construction of a plant at Oyster Creek, New Jersey, at a guaranteed fixed price that was clearly competitive with coal and oil fired alternatives. By 1967, US utilities alone had ordered more than 50 power reactors, with an aggregate capacity larger than that of all orders in the USA for coal and oil fired plants, and from 1967-1974 they placed an additional 196 orders. The US Atomic Energy Commission foresaw 1000 nuclear plants on line in the USA by the year 2000.[18] Globally the nuclear industry started to surge up the early slope of the S-shaped curve of global installed nuclear capacity shown in the left panel of Figure III.2.

The turnkey plants in the USA successfully attracted utilities to nuclear power and gained their manufacturers a strong domestic foundation from which they then expanded internationally. But every turnkey plant lost its manufacturer money.[19] The losses were due only partly to aggressively competitive low bidding. They also reflected a rapidly changing licensing environment that increased costs. In this sense the timing of the turnkey plants could hardly have been worse.

C. Environmentalism, Slower Growth and Bad Management

Oyster Creek was completed in 1969, and subsequent turnkey plants stretched into the 1970s. Increasing challenges by a growing number of mainly environmentalist nuclear opponents began to stretch out licensing times and sometimes necessitate design changes, thereby delaying cost recovery, increasing costs, and complicating financing. The first Earth Day in the USA took place in 1970, and the National Environmental Policy Act was passed in 1969. It created new requirements (notably an 'environmental impact statement') and new institutions (the Environmental Protection Agency and Council on Environmental Quality). All the trends of the time in the USA conspired to increase the numbers, opportunities, and credibility of nuclear opponents.

The environment was changing in Europe as well. The 1970s saw a surge in environmentalism, resulting in new environmental legislation, environmental ministries and, in several countries, the founding of formal Green political parties, all anti-nuclear.

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[18] Cohn (1997) p. 127

[19] Simpson (1995) pp. 192-194

In the USSR the main environmental challenge to nuclear expansion would come later, after the 1986 Chernobyl accident. Throughout the 1970s and early 1980s expectations still remained high, with a target of 100 GW(e) to be installed by 1993.

Even in the West, the changed licensing environment took a while to affect the flow of new orders. At the beginning of the 1970s orders rose steadily. But by 1975, the curve of orders had already passed its peak. From 1974 to 1975 orders dropped abruptly from 75 GW(e) to 28 GW(e). Moreover, all 41 reactors ordered after 1973 were subsequently cancelled, and, indeed, more than two-thirds of all nuclear plants ordered after January 1970 were eventually cancelled.[20] The IAEA's *Annual Report for 1975* called the decline temporary, attributing it to economic recession, rising capital and fuel costs and environmental concerns. The combination of inflation and rising energy costs, in particular, both depressed growth in electricity demand (and thus utility revenues) at the same time that they increased utility costs. A more lasting, but less immediately apparent effect, was the slow and continuing decoupling of economic growth from energy and electricity growth. As the ratio of electricity consumption to GDP decreased, growth forecasts and orders that had assumed the ratio would never change became untenable.

Towards the end of the 1970s the shrinking flow of nuclear power orders in the USA dried up completely, and it has not revived. The most obvious cause was the Three Mile Island accident on 28 March 1979, the first major accident at a civilian nuclear power station. The psychological effect on the population

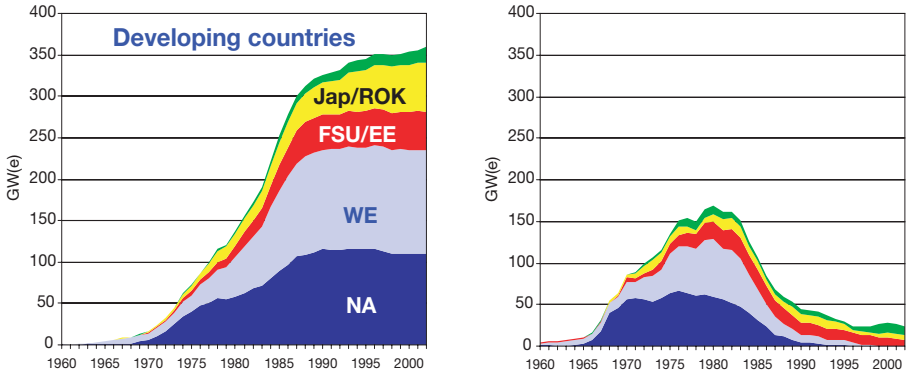

FIG. III.2. The left panel shows growth in global installed nuclear capacity in GW(e). The right panel shows the capacity under construction worldwide, also in GW(e). FSU: Former Soviet Union; EE: Eastern Europe; NA: North America; Jap: Japan; ROK: Republic of Korea; WE: Western Europe.

[20] Cohn (1997) p. 127

in the neighbourhood, and eventually throughout the Western world, was immense. So was the damage to the plant itself and to the reputation of the nuclear power industry. In 1979, the total capacity of nuclear power plants on order worldwide actually decreased by about 8000 MW(e); eight new plants were ordered but 14 previous orders were cancelled, and in subsequent years, US utilities continued to cancel orders they had already placed.

Not all of nuclear's diminishing popularity in the 1970s and 1980s could be laid at the feet of external forces. A big contributor to high costs was the inability in many cases of utilities, equipment suppliers, contractors and regulators to rise to the management challenges of the new technology.

The downturn in orders in the 1970s slowed the build-up of global nuclear capacity and eventually led to a flattening after 1985 of the capacity curve shown in the left panel of Figure III.2. As growth slowed, calculations about the long term evolution of nuclear energy and the relative near term economic attractiveness of particularly breeder reactors and the closed fuel cycle began to change. The initial rapid expansion of nuclear capacity – at an average rate of 30% annually in the first half of the 1970s – and a very conservative understanding of the long-term availability of uranium resources, had made breeders and reprocessing appear almost essential. The argument for breeders and reprocessing was especially strong in countries with limited uranium resources, such as France, Japan, the UK and India.

Breeders were hardly exotic. The first nuclear electricity had been produced by a fast breeder reactor EBR-I in 1951, and in 1959 the Russian BR-5 fast neutron reactor reached its design capacity of 5 MW(e) at Obninsk. The UK completed the 14 MW(e) Dounreay fast breeder reactor in 1962, and in 1963 the USA completed the 61 MW(e) Fermi fast breeder reactor. In 1973 France connected the 250 MW(e) Phénix to the grid and the USSR did the same for the 350 MW(e) BN-350, at Shevchenko (now Aktau in Kazakhstan). BN-350 went on to provide both electricity and desalinated water for Aktau city and neighbouring industries for 26 years before being shut down only in 1999. In 1975 the UK completed the 250 MW(e) Dounreay prototype fast reactor. In 1980 the commercial sized BN-600 (600 MW(e)) was connected to the grid in the USSR, and in 1986 the Superphénix at Creys-Malville, rated at 1242 MW(e), was connected to the French grid. India's 13 MW(e) fast breeder test reactor went critical in 1985, and, finally, in 1994 Japan commissioned the 280 MW(e) Monju fast breeder reactor, although a sodium leak in December of the following year has kept it out of operation ever since.

Economic incentives for breeders and reprocessing have diminished with the slow down in capacity growth since the 1970s. But they have also diminished because estimates of uranium resources have continually risen – a rise both driven by, and reflected in, the evolution of uranium prices shown in

Figure III.3. Rapid capacity growth in the early 1970s pushed up prices, which in turned encouraged exploration. Greater exploration increased resource estimates, which, along with the slowdown in growth, gradually depressed prices.

The changed economic incentives for closing the fuel cycle have limited the introduction of breeder reactors to the units listed above and to continuing research and development programmes in France, Japan, Russia, India, the Republic of Korea and China. They have also limited the need for fuel reprocessing. France has two large facilities at La Hague, and the UK and Russian Federation each have one. Smaller facilities operate in India (three) and Japan (one).

About one third of the spent fuel discharged from power reactors is reprocessed; the rest is in interim storage. By the end of 2000, reprocessing had separated 200 tonnes of plutonium from civilian spent fuel – about 20% of the total amount of plutonium discharged from civilian reactors. Some of the recovered plutonium and uranium has been mixed with fresh uranium to create MOX fuel for LWRs.

Out of the diversity of initial designs, LWRs have gradually come to dominate the market. In the late 1960s the French authorities abandoned the gas graphite cycle and turned to LWRs. In the late 1980s, the UK followed suit

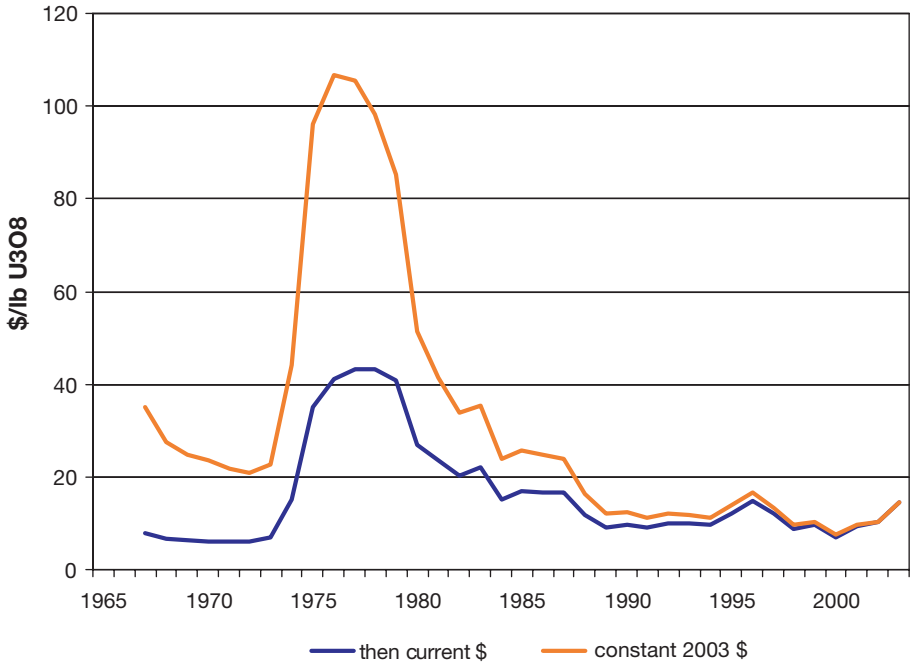

FIG. III.3. Uranium Prices, 1967-2003.

with its first order for an LWR. In the meantime the UK had built a number of advanced gas cooled reactors and had experimented with other designs. As noted above the USSR built two types of power reactors, both using enriched uranium fuel. These were LWRs in its WWER series and the graphite moderated, pressurized water cooled RBMK (reactor bolshoi moshchnosty kanalny – high power channel reactor). The first industrial scale WWER reactor, Novovoronezh-1, came on-line in 1964, as did the first industrial scale water cooled, graphite moderated reactor, Beloyarsky-1. The USSR also exported WWER light water power reactors.

D. The 1990s

As shown in Figure III.2, trends since 1990 are characterized by slow but continuing capacity growth, new construction dropping to zero in North America and Western Europe, and modest continuing construction elsewhere. Growth in nuclear electricity *generation* has been somewhat greater than Figure III.2's growth in nuclear *capacity*, as management efficiencies in the 1990s have steadily increased the average availability factors of the world's nuclear plants (see Figure III.4).

In the left panel of Figure III.2, the capacity curves for North America, Western Europe and Russia and Eastern Europe are essentially flat. Two

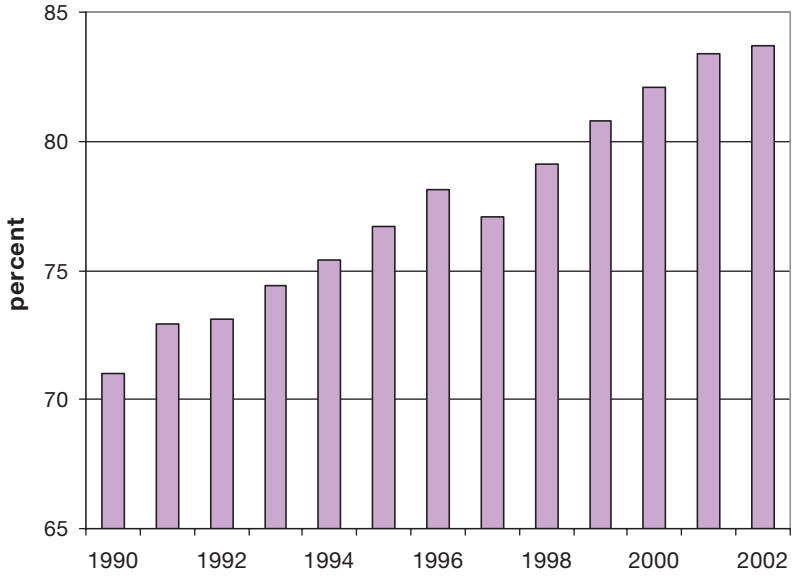

FIG. III.4. Increases in the average energy availability factor of nuclear power plants worldwide since 1990.

reasons are the 1986 Chernobyl accident and electricity market deregulation in many countries. Ironically, both these reasons, plus consolidation in the nuclear industry, also help explain the rising availability factors shown in Figure III.4.

As noted above, there had already been a decade of significant opposition to nuclear power in Europe. Austria in 1978 had rejected nuclear power in a general referendum, opposition had stopped Ireland's attempt at nuclear development in the late 1970s, and in 1980 Swedish voters approved a referendum to phase out the country's twelve (now eleven) operating nuclear power plants. But Chernobyl broadened the opposition to nuclear power. Italy, for example, voted in 1987 to shut down all four of its NPPs. Russia's nuclear expansion was also stalled.

Another factor was electricity market deregulation in particularly OECD countries. In the USA deregulation began in 1978 with the requirement that utilities buy electricity from qualified independent producers, but open access to transmission networks, competition at the wholesale level, and competition at the retail level were only introduced in the 1990s. Today about half of US states have full competition at the retail level. In Europe, deregulation began in the early 1990s with the Scandinavian countries first liberalizing and then privatizing the energy industry. In the UK the full process took a decade, beginning with the UK Electricity Act in 1989 and reaching full deregulation in 1999. The European Union directive to establish common rules for an internal electricity market was adopted in 1996, with an implementation deadline of February 1999. Proposed next steps would open the electricity market for all non-household customers by July 2004, and for all customers by July 2007. In Japan, initial steps were taken in 1995 with an amendment to the electric utilities law to allow independent power producers (IPPs) into the wholesale market.

Deregulation 'exposed' excess capacity that had accumulated in regulated markets, pushed electricity prices (and thus utility revenues) lower and made power plant investments more risky. No longer could regulators guarantee rates that would assure cost recovery and profitability. Excess capacity reduced demand for new capacity – of any sort – and the emphasis on rapid reliable returns made nuclear power's 'front-loaded' cost structure, with high initial capital costs and low operating costs, an important disadvantage. Because nuclear plants are offered in large units (to benefit from economies of scale), have longer construction times than alternatives, and have organized opposition to regulatory approval, they present more of an investment risk than particularly new natural gas fired capacity. These differences, coupled with low gas prices through most of the 1990s and natural gas' image as a clean burning fuel, steered new investments away from nuclear and most often in the direction of natural gas.

But the 1990s were also characterized by the rising availability factors in Figure III.4. The Chernobyl accident was one motivation. It fostered information exchange, comparison, emulation of best practice and communication among operators and regulators facilitated by IAEA, OECD/NEA, World Association of Nuclear Operators and others. The comprehensive exchange of information on operational safety experience in particular has become a major factor in nuclear safety improvements worldwide, and a safer power plant is generally a more available, and more profitable, power plant. At the same time deregulating markets meant that increased availability translated increasingly directly into increased profits. Selected companies moved to define themselves largely by the size and expertise of their nuclear operations, leading to consolidation in the industry and more nuclear plants being operated by those who did it best.

The final characteristic of the 1990s is the shift towards Asia and developing countries. As discussed in Annex II, current expansion is centred in Asia. One reason is that new nuclear power plants are most attractive where energy demand growth is rapid, alternative resources are scarce, energy supply security is a priority or nuclear power is important for reducing air pollution and greenhouse gas (GHG) emissions. One or more of these features characterize China, India, Japan and the Republic of Korea, where most current construction is taking place.

Of the developing countries, India has the longest history while China has the greatest nuclear capacity. Because India has poor uranium resources but substantial thorium, its strategy since the beginning (an Atomic Energy Commission was established as early as 1948) has been aimed at the eventual use of thorium. The sequence was to start with natural uranium reactors to produce electricity and plutonium, use the plutonium in fast breeders to breed more plutonium and uranium-233 from thorium, and then use uranium-233 to sustain breeders converting thorium to uranium-233.

Nonetheless, India's first two nuclear units to be connected to the grid, at Tarapur in 1969, were GE BWRs, offered as turnkey plants. But all twelve units since have been PHWRs, as are six of eight units under construction. The other two are WWERs.

China is the most recent developing country to adopt nuclear power, with its first industrial sized nuclear power plant at Guangdong-1 being connected to the grid in 1993. Since then it has built an additional six units with four more under construction. As noted in the main body of this report, the future of nuclear power may be largely determined by its future in countries like India and China – countries with large populations, large prospective increases in GDP and energy demand, established and expanding nuclear expertise, but a still only minor share of nuclear power in the electricity supply.

REFERENCES

[1] Steven Mark Cohn, *Too Cheap to Meter: An Economic and Philosophical Analysis of the Nuclear Dream*, State University of New York Press, Albany, NY, 1997.

[2] David Fischer, History of the International Atomic Energy Agency: the first forty years, IAEA, Vienna, Austria, 1997.

[3] David Hart, Nuclear Power in India: A Comparative Analysis, George Allan & Unwin, London, 1983.

[4] Harry Henderson, Nuclear Power, ABC-CLIO, Inc., 2000.

[5] International Atomic Energy Agency (IAEA), Department of Nuclear Energy, Division of Nuclear Power, "Time-line of Nuclear Power in The World", unpublished, 2002.

[6] Paul R. Josephson, Red Atom, W.H. Freeman and Company, New York, 2000.

[7] Colin Keay, "A perspective on Nuclear Energy," referenced in http://www.world-nuclear.org/opinion/razorfeb02.htm, World Nuclear Association, London, February 2002.

[8] Rick Michal (2000), "Richard Rhodes on nuclear technology," *Nuclear News*, July 2000.

[9] Rick Michal (2001), "Fifty years ago in December: Atomic reactor EBR-I produced first electricity," *Nuclear News*, November 2001.

[10] Judith Perera, *Nuclear Power in the Former Soviet Union, Volume 2: Nuclear Fuel Cycle Facilities*, The McCloskey Group Ltd, Petersfield, Hampshire, UK, 2002.

[11] Richard Rhodes, *Nuclear Renewal*, Viking Penguin, New York, 1993

[12] Richard Rhodes, "Changing perspectives on nuclear energy," *Nuclear News*, July 2000.

[13] John W. Simpson, *Nuclear Power from Underseas to Outerspace*, American Nuclear Society, La Grange Park, Illinois, USA, 1995.

[14] Peter Stoler, *Decline and Fail*, Dodd, Mead & Company, NY, 1985.

[15] Joseph P. Tomain, *Nuclear Power Transformation*, Indiana University Press, Bloomington, Indiana, USA, 1987.

[16] Karl Winnacker and Karl Wirtz, *Nuclear Energy in Germany*, American Nuclear Society, La Grange Park, Illinois, 1979.

[17] World Nuclear Association (WNA), "Outline History of Nuclear Energy," http://www.world-nuclear.org/info/inf54.htm, WNA, London, February 2002.

ANNEX IV: ADVANCED AND INNOVATIVE TECHNOLOGIES

In response to the challenges currently facing nuclear power as outlined in Section B.1, many countries are working on advanced reactor – fuel cycle systems to improve their economics, safety and proliferation resistance. With regard to advanced NPP designs, efforts focus particularly on making plants simpler to operate, inspect, maintain and repair. Safety improvements include features to further reduce the likelihood of accidents, to allow operators more time to assess developments before acting, and to provide ever greater protection against any possible releases of radioactivity to the environment.

There are two basic categories of advanced designs. *Evolutionary designs* improve on existing designs through small or moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risk. Evolutionary designs incorporate improvements based largely on feedback from experience and the incorporation of new technological achievements, plus the possible introduction of some innovative features, e.g. passive safety systems. *Innovative designs* incorporate radical conceptual changes in design approaches or system configuration. They generally require substantial R&D, feasibility tests, and a prototype or demonstration plant.

In the near term, most new NPPs are likely to be evolutionary designs building on proven systems while incorporating technological advances and often economies of scale. For the longer term, the focus is on innovative designs, several of which are in the small-to-medium range (less then 700 MW(e)). These envision construction using factory built components, including complete modular units for fast on-site installation, creating possible economies of series production instead of economies of scale. Other advantages foreseen for smaller units are easier financing, their greater suitability for small electricity grids or remote locations, and their potential for district heating, seawater desalination and other non-electric applications. All should increase their attractiveness for developing countries.

The summary below of current developments categorizes designs according to reactor type: water cooled reactors (both LWRs and HWRs), gas cooled reactors and fast reactors that use liquid metal (e.g. sodium) or gas (e.g. helium) as a coolant.

A. Light Water Reactors (LWRs)

LWRs make up 80.5% of all NPPs in operation and are thus a natural focus for evolutionary design improvements. The principal large evolutionary designs are the ABWR (advanced boiling water reactor) and the ABWR-II of Hitachi and Toshiba in Japan and General Electric (GE) in the USA; the APWR (advanced pressurised water reactor) of Mitsubishi in Japan and Westinghouse of the USA and the APWR$^+$ of Mitsubishi; the BWR 90+ of Westinghouse Atom of Sweden; the EPR and the SWR-1000 of Framatome ANP from France and Germany; the ESBWR of GE; the AP-1000 of Westinghouse in the USA; the WWER-1000 of Atomenergoproject and Gidropress, Russia; the KSNP$^+$ and the APR-1400 of Korea Hydro and Nuclear Power and the Korean Nuclear Industry; and the CNP-1000 of the China National Nuclear Corporation.

The main small and medium-size evolutionary LWR designs are the AP-600 and the integral IRIS designs of Westinghouse; the WWER-640 of Atomenergoproject and Gidropress, the PAES-VBER of the Experimental Design Bureau for Machine Building (OKBM) and the VK-300 of RDIPE, all from Russia; the HSBWR and HABWR design concepts of Hitachi; and the NP-300 of Technicatome in France.

Two ABWRs are operating at TEPCO's Kashiwazaki-Kariwa site, and ten more are under construction or planned.[21] In December 2003, Teollisuuden Voima Oy (TVO) of Finland signed a turnkey contract with Framatome ANP and Siemens AG for an EPR for the Olkiluoto site. In the Republic of Korea, the first KSNP$^+$ units are planned for Shin-Kori-1 and -2 with construction to start in 2004 and 2005 respectively. Two APR-1400 units are also planned for Shin-Kori, with construction of the first to start in June 2005. For the AP-1000, Westinghouse submitted an application to the US NRC in March 2002 for Final Design Approval and Design Certification. The Final Design Approval is expected in 2004 and Design Certification is expected in 2004 or 2005. For IRIS, Westinghouse plans to submit a Design Certification application in 2005, with the objective of approval by 2008 or 2009. In 2002 the ESBWR design and technology base were submitted to the US NRC as a first step toward Design Certification. For Framatome's SWR-1000, the pre-application phase for Design Certification by the US NRC started in 2002.

For innovative LWR designs, SMART in the Republic of Korea and CAREM in Argentina are both integral primary system designs, and both plan verification and prototype or demonstration plants prior to commercial

[21] Two ABWRs are under construction in Taiwan, China.

deployment. Examples of innovative LWRs designed particularly to achieve a high conversion ratio in converting fertile isotopes to fissile isotopes are the RMWR of the Japan Atomic Energy Research Institute (JAERI) and the RBWR of Hitachi. Thermodynamically supercritical water cooled systems (SCPR) are being developed within the framework of GIF, and will most likely require a prototype or demonstration plant.

B. Heavy Water Reactors (HWRs)

HWRs account for about 8% of operating NPPs. Their special features are that they can be fueled with natural uranium due to their good neutron economy made possible by using heavy water as the moderator, and that they can be kept operating during refueling.

Atomic Energy of Canada Limited's (AECL's) evolutionary CANDU design, the ACR-700, retains the general reactor characteristics and power levels of the current CANDU-6 and CANDU-9, while aiming to improve the economics through plant optimization and simplification. New features in the ACR-700 are its use of slightly enriched uranium and light water coolant. It is currently undergoing a pre-application licensing review by the US NRC, after which AECL intends to seek a Design Certification in 2005. It is simultaneously undergoing a licensing review in Canada.

Within the framework of GIF, AECL is developing an innovative design, the CANDU-X, which would use supercritical light water coolant to achieve high thermodynamic efficiency.

India has made regular evolutionary improvements to its HWR designs ever since its initial units at Rajasthan-1 and -2. In 2000 construction began on two larger 490 MW(e) units at Tarapur. India is also developing the Advanced Heavy Water Reactor (AHWR), a heavy water moderated, boiling light water cooled, vertical pressure tube type reactor, that includes passive safety systems and is designed for optimal thorium use.

C. Gas Cooled Reactors (GCRs)

Gas cooled reactors – both CO_2 cooled Magnox reactors and advanced gas cooled reactors (AGRs) – dominate nuclear electricity production in the UK. There is a long history of R&D on high temperature reactors (HTGRs) with helium as the coolant and graphite as the moderator, and prototype and demonstration plants using the Rankine steam cycle have also been built and operated. Distinctive features of HTGRs include the coated particle fuel

design, which acts as a barrier against fission product release, and a low power density, high heat capacity core that increases safety.

There is considerable current effort devoted to gas turbine direct Brayton cycle helium cooled designs that promise high thermal efficiency and low generation costs. Eskom, South Africa's Industrial Development Corporation, and British Nuclear Fuels (BNFL) are jointly developing a pebble bed small modular HTR (PBMR) system. Also, the Russian Ministry of Atomic Energy, OKBM, General Atomics, Framatome and Fuji Electric are jointly developing a small gas turbine modular helium reactor (GT-MHR). This is designed for electricity production using weapons grade plutonium.

The high temperatures made possible by the inert helium coolant and coated fuel particles are well above those possible in water cooled reactors, and have prompted research for a number of high temperature heat applications such as hydrogen production. HTGRs also have potential for low temperature heat applications such as seawater desalination by providing steam produced by the waste heat. Currently two helium cooled test reactors are in operation, the High Temperature Engineering Test Reactor (HTTR) at JAERI in Japan and the HTR-10 at the Institute of Nuclear Energy Technology (INET) in China. A helium cooled very high temperature reactor (VHTR) is being developed within the framework of GIF with a focus on hydrogen production. Similar independent efforts are ongoing in Russia with the Minatom's OKBM taking a lead.

D. Fast Reactors

Liquid metal cooled fast reactors (LMFRs) have been under development for many years, primarily as breeders. They have accumulated more than 200 reactor-years of operational experience based on successful designs including the small Prototype Fast Reactor in the UK, the prototype Phénix fast reactor in France, the BN-350 in Kazakhstan (which produced electricity and desalinated seawater), BN-600 in Russia, Monju in Japan, and the 1200 MW(e) Superphénix in France. In addition, there is a considerable base of experience with lead-bismuth eutectic cooled propulsion (submarine) reactors built and operated in the former USSR.

Fast reactors use fast neutrons for sustaining the fission process and can simultaneously convert plentiful fertile isotopes of uranium or thorium into fissile isotopes that can be used for fuel. Plutonium breeding allows fast reactors to extract 60-70 times as much energy from uranium as do thermal reactors. In addition, fast reactors could potentially help reduce plutonium stockpiles, and reduce the required isolation time for high level radioactive

waste by making use of transuranic radioisotopes and transmuting some of the most cumbersome long lived fission products.

Current LMFR activities include the construction in China of the small Chinese Experimental Fast Reactor (CEFR) with first criticality scheduled for the end of 2005; the development of the small KALIMER design in the Republic of Korea; the successful operation of the Indian Fast Breeder Test Reactor (FBTR), especially for fuel irradiation and materials research; the development of the medium size Prototype FBR (PFBR) in India for which construction started in the final quarter of 2003; Japanese initiatives to restart Monju; the Japan Nuclear Cycle Development Institute's 'Feasibility Study on a Commercialised Fast Reactor Cycle System'; efforts in Russia to complete the BN-800 reactor at Beloyarsk by 2010; the 2003 restart of Phénix in France, principally for experiments on long lived radioactive nuclide incineration and transmutation; and several design studies around the world of advanced fast reactors having improved economics and enhanced safety.

Development activities are underway in GIF on lead alloy and sodium liquid metal cooled fast reactor systems and on gas (helium) cooled fast reactors (GFR) with an integrated fuel cycle with full actinide recycle. Similar efforts are ongoing in Russia.

Research on fast neutron spectrum hybrid systems (e.g. accelerator driven systems (ADS)) is also underway in several countries. The potential advantages of ADS systems are low waste production, high transmutation capability, enhanced safety characteristics and better long term utilization of resources (e.g. with thorium fuels). ADS research activities include the development of the HYPER concept by the Republic of Korea, plus design studies and research on basic physical processes in Russia, in eight EU countries and in the US Advanced Accelerator Applications Program (recently merged with the Advanced Fuel Cycle Initiative).

E. International Initiatives for Innovative Designs

Complementing the many initiatives above are two major international efforts to promote innovation, the Generation IV International Forum (GIF) and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

The US Department of Energy's Office of Nuclear Energy, Science and Technology has for several years promoted development to move beyond Generation II reactors (today's commercial power stations) and Generation III reactors (the currently available advanced LWRs) to the next generation, Generation IV. The initiative led in 2000 to the establishment of GIF, an

international effort to jointly define the future of nuclear energy research and development. Members of GIF are Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the UK, the USA and Euratom. The IAEA and the OECD/NEA have permanent observer status in the GIF Policy Group, which governs the project's overall framework and policies.

The objective as stated in the GIF charter is "the development of concepts for one or more Generation IV nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide a competitively priced and reliable supply of energy to the country where such systems are deployed, while satisfactorily addressing nuclear safety, waste, proliferation and public perception concerns". GIF began with an evaluation of an extensive, wide ranging collection of concepts. In 2002, the GIF Policy Group selected six of these for future bilateral and multilateral cooperation, and defined a 'technology roadmap' to help prepare and guide subsequent research and development. The six selected systems are:

- gas cooled fast reactor systems,
- lead alloy liquid metal cooled reactor systems,
- molten salt reactor systems,
- sodium liquid metal cooled reactor systems,
- supercritical water cooled reactor systems, and
- very high temperature gas reactor systems.

The IAEA's INPRO has as its main objectives, first, helping to ensure that nuclear energy is available to contribute to fulfilling energy needs in the 21st century in a sustainable manner and, second, bringing together technology holders and technology users to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles. As of September 2003, members of INPRO included Argentina, Brazil, Bulgaria, Canada, China, France, Germany, India, Indonesia, the Republic of Korea, Pakistan, the Russian Federation, South Africa, Spain, Switzerland, the Netherlands, Turkey and the European Commission.

In its first phase, INPRO outlined the prospects and potential of nuclear power and prepared guidelines for evaluating innovative concepts for both nuclear reactors and fuel cycles. These guidelines include 'user requirements' for innovative nuclear energy systems, covering the areas of economics, sustainability and environment, safety, waste management, and proliferation resistance. They also outline a method (the 'INPRO methodology') for applying INPRO user requirements to specific designs and concepts. In addition, INPRO has produced recommendations on cross-cutting

infrastructural, institutional, legal, social and human resource issues affecting the evolution of nuclear power.

In July 2003, INPRO entered a new stage focussed on validating the INPRO methodology through test applications in a series of case studies. The results will be used to update and sharpen the user requirements and methodology, which will then be generally available for applications by Member States and others to evaluate proposals and guide nuclear R&D strategies.

F. Fusion

Nuclear fusion requires much higher temperatures than nuclear fission – on the order of 10^6 degrees Kelvin. At such high temperatures, the nuclear fuel is in a 'plasma state' of free nuclei (ions) and electrons, and special techniques are needed to confine the plasma since no materials can withstand the heat. There are two major confinement concepts, magnetic (tokomak) and inertial. The International Thermonuclear Experimental Reactor (ITER), which is the focus of much of today's experimental and theoretical fusion research, uses magnetic confinement. ITER's purpose is to demonstrate plasma burning and, although ITER itself will not generate electricity, to show that electricity generation from fusion can be safe and environmentally attractive. More specifically, it is designed to generate 500 MW of fusion energy per pulse, with each pulse expected to last several minutes. The amount of energy generated is expected to be at least ten times higher than the amount of input energy needed to run the reactor.

Currently ITER's Engineering Design Activities stage has been completed, and the project is nearing a decision on site selection. In 2003 ITER gained three new members and lost one. The new members are the USA, which had originally left ITER back in 1999, China and the Republic of Korea. Canada withdrew from ITER in December 2003. That makes six members in total, the other three being the European Union, Japan and Russia. The two site proposals still under consideration are in France (Cadarache) and Japan (Rokkesho-muro). Following a final decision on the site, the next step is establishing the ITER International Fusion Energy Organization, anticipated for 2004, which will then carry the project forward.

Research also continues on other magnetic confinement approaches such as stellarators, compact tori and reversed field pinches, which also expands the basic understanding of plasma physics and fusion.

Inertial confinement is being developed intensively by national programmes in the USA and France. The National Ignition Facility at the University of California's Lawrence Livermore National Laboratory, which is

scheduled for completion in 2008, will be a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, 351-nm laser system together with nearly 100 experimental diagnostics. Operational testing for several of the beams has already been completed.

ANNEX V: MOLECULAR TECHNOLOGY - A PRACTICAL REVOLUTION

A. Introduction

Many tremendous and exciting advances are taking place within the biological field, facilitated by numerous biotechnological developments and applications. These have enabled scientists to approach old problems in new and innovative ways as well as allowing them to find unique solutions for various biological, medical, and agricultural needs. The developments have already started to make an impact on society. These technological advances have led to the increased sensitivity and specificity of test assays, the miniaturisation of instrumentation and development of point-of-care devices. This has strengthened and encouraged the development of a strong knowledge base on the ground. An example is '$^{35}S/^{32}P$ phospho-imaging gene sequencing' (a technique that uses isotopes to produce rapid and sensitive images), which is now considered a cost effective and implementable technology in several developing countries. In addition, generic molecular and related isotopic techniques such as southern blots, northern blots, two-dimensional electrophoresis, DNA macro- and micro-arrays and others are equally applicable to the medical and agricultural fields.

B. Isotopic Methods

Isotopic methods have played an integral part in the development of molecular biology since its inception many decades ago. Despite the emergence of various alternatives with their associated advantages, both non-stable and stable radioisotopes are still used by dedicated users for established applications and still continue to attract new converts. The high sensitivity and low detection limits unique to isotopic labelling were the main driving forces behind the commercial development of more user-friendly equipment. Radioisotopes represent one of the main detection systems used in molecular biology, hence the emphasis given in this report. Nevertheless, it has to be realized that the current advances in molecular technology span the whole discipline, including the development of numerous alternative approaches.

C. Genomics

The term 'genomics' was coined some 20 years ago to define the study of genes and their functions. It followed the development of various technologies and instrumentation required to determine the nucleotide sequences of entire genomes, during the late 70s and early 80s. The DNA sequence is often referred to as the 'blueprint of life' and the impact of its elucidation over the last few decades has been compared to that of the discovery of the periodic table in chemistry. Initially, sequence determination was limited to the simplest organisms such as viruses possessing not more than 16 genes. In 1990, the most ambitious scientific endeavour in the history of life sciences was launched, viz. the sequencing of the full human genome thought to contain about 100 000 genes. This enormous task was completed in 2000 at a cost of $3 billion. The full genome sequences of the rat, mouse and some pathogenic micro-organisms are now also available and similar studies on a variety of other organisms such as cattle, chickens, sheep, goats and pigs are in progress.

Following the successful sequencing of the human genome there has been a flurry of activity, mainly by multinational biotechnology companies, to identify and patent genes with possible applications in human medicine and agriculture. This reflects the growing awareness among scientists and investors of the enormous potential within this field, both for further scientific discoveries as well as future financial profits.

D. Molecular Diagnostics

One area that has been escalating exponentially is molecular diagnostics with its associated commercialization. The term molecular diagnostics was coined to distinguish diagnostic techniques that depend on gene sequences from the more conventional *in vitro* tests - a field in which the Agency has been particularly active. In the USA, for example, the demand for molecular diagnostic testing has increased by 600% over the past two years. Molecular detection can contribute significantly to improved disease management and control in various ways. The polymerase chain reaction (PCR) has revolutionized this field and is being increasingly implemented in developing as well as developed countries, with significant assistance by the Agency in many cases.

E. Medical Applications

There are numerous conventional laboratory diagnostic assays for human infectious diseases that are often slow, relatively insensitive, non-specific, require invasive clinical procedures and often do not provide quantitative information. In the case of *M. leprae, M. tuberculosis* and *Chlamydia*, the infectious agent is either uncultivable or difficult to culture. Molecular detection methods can provide not only definitive identification but also differential diagnosis of the etiologic agent(s), as with respiratory infections due to *Legionella* and *Mycoplasma pneumoniae* where clinical features and serology are uninformative. This information is essential for the prompt institution of appropriate treatment. In the case of *Herpes simplex* and *Chlamydia trachomatis* infections, PCR-based detection is currently being considered as the possible gold standard. In the human health sector, genes or gene groups have already been identified that are involved in genetic diseases such as cystic fibrosis. For thalassemia, out of a spectrum of 200 mutations about 10 are responsible for 90% of the disease in any one country. In Cyprus for example, simplified diagnostic algorithms have been established and national genetic counselling programmes have been established.

F. Livestock Applications

In animal health also, the partial sequencing of the genomes of important pathogens ('gene sequencing' as opposed to 'genome sequencing') is already widely used to study the epidemiology of disease outbreaks, by inter alia determining the origin of infection. This has contributed significantly to limiting disease spread, as was the case with recent foot and mouth disease outbreaks. In addition, PCR can differentiate between the S19 *Brucella abortus* vaccine strain and wild-type organisms within hours compared to the classical microbiological test, which could take several weeks. Similarly, micro-satellite analyses are used extensively in parentage verification, for the identification of individuals, in the study of population genetics in various animal and plant species and in the conservation of livestock breeds or wildlife species. Genome sequencing of infectious agents has also served as an aid in understanding the causes of disease, where epidemics originate and in improving their control. The detection of drug resistant strains of *Mycobacterium tuberculosis* is being effectively achieved using PCR-dot blot hybridization and ^{32}P radiolabelled probes, or micro-arrays that allow for the batch analysis of samples. In South Africa, 90% of all multi-drug resistant tuberculosis (MDR-TB) cases can

be detected in five days by screening for just three codons directly from sputum, as opposed to conventional methods that can take eight weeks.

The identification of genes responsible for natural resistance to diseases could lead not only to an improvement in agricultural resource management, but also in the selective breeding and cloning of resistant animals and plants, thereby enhancing or replacing conventional methods of disease control. One of the most important trends with an added market potential is termed molecular breeding, i.e. the application of genomics to the breeding of animals and plants with desired genetic traits. The natural resistance to specific diseases, found in individual animals or local breeds can be used to develop resistant breeds for example. Several genes and traits have already been identified and sequenced and can be used for this purpose. It has been shown, for example, that the incidence of resistance to brucellosis in a cattle herd can be raised within one generation from 18% to almost 53.6% by breeding with parents that tested positive for the 'brucella resistance gene'. Total resistance may not be achievable, but partial resistance would enhance effective disease management. Another area of potentially important significance is an improvement in the utilization of low-grade forage by ruminants through the transfer of specific genes to ruminal bacteria, which could have important agricultural and economic impacts in certain marginal areas.

G. Biochips

In the health sector, the most important application will be the development of diagnostic kits capable of detecting multiple infective agents in a single, highly sensitive, specific and fast assay e.g. biochips. Such tests can also be adapted for field use that would reduce costs considerably, always an important consideration in veterinary diagnostics. The high sensitivity of such assays also means that an infection could be diagnosed in an animal before any symptoms are seen, a great advantage where an epidemic needs to be controlled. In addition, due to its specificity and sensitivity, molecular technology lends itself readily for early warning systems. It is anticipated that a single biochip could be developed for each species, allowing for the detection of all relevant infectious agents. At least one pharmaceutical company is actively pursuing the development of a 'backpack' laboratory for field use especially in developing countries. A further refinement combining molecular diagnostics with micro-array nanotechnology, allows for the simultaneous detection of deviations in thousands of genes using a single glass 'chip' with immobilized probes and fluorescence-based detection. This technology, however, remains out of the reach of most diagnostic laboratories due to the prohibitive cost of

equipment (about $200 000). In such settings, a relatively cost-effective method using nylon macroarray chips and radioisotopic (autoradiographic) detection using phosphor-imaging, is a viable alternative. This is amenable to small-scale automation.

H. Biopharmaceuticals

By studying the genetic basis for the individual variation in response to specific drugs, the most suitable therapy for an individual can be selected to avoid unwanted side-effects. Such information can also be used in drug discovery and in developmental strategies such as the design, development and production of new or improved biopharmaceuticals for the treatment of diseases. Despite its tremendous potential, the molecular design, development and production of biopharmaceuticals has not been fully realized as most existing recombinant products are naturally occurring human proteins. Of these, only a growth hormone has found wider application as a stimulant of milk production in dairy cattle. Some progress is being made in achieving acceptance in the community, as seen with the approving of an antisense oligonucleotide drug, fomivirsen, for the treatment of cytomegalovirus retinitis, an opportunistic infection associated with HIV/AIDS.

I. Scintillation Proximity Assay

Scintillation proximity assay (SPA) was commercially introduced in 1991 as a rapid and sensitive assay with the capability of high-throughput screening of a wide variety of molecular interactions within a homogeneous system. It utilizes microscopic beads containing a scintillant that can be stimulated to emit light. This stimulation event only occurs when radiolabelled molecules of interest (^{3}H or ^{33}P) are bound to the surface of the bead. SPA is a versatile system and applications include analyses of receptor-ligand binding, enzyme assays, radioimmunoassays, protein-protein and protein-DNA interactions. It is used widely by the drug industry for drug design and discovery. Another important application of SPA is in the detection of enzyme activity. The basic assay involves substrate capture on SPA beads. If an enzyme acts on this substrate, it leads to addition or removal of the radioisotope, which results in a corresponding increase or decrease in signal from the bead. Applications include the screening of drugs that target enzyme function e.g. to screen antiviral drugs that inhibit viral enzymes.

J. Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) spectroscopy uses high magnetic fields and radio-frequency pulses to manipulate the spin states of nuclei - including the stable isotopes ^{1}H, ^{13}C and ^{15}N. A NMR spectrum can be obtained of a molecule incorporating such nuclei and can then indicate its structure. The accuracy of NMR spectroscopy for protein-structure analysis is comparable to that of X-ray crystallography. NMR-based screening has become an important tool in the pharmaceutical industry, especially for methods that provide information on the location of small molecular binding sites on the surface of a drug target. In this regard, NMR and X-ray crystallography act synergistically.

K. Vaccines

Prevention and control of disease epidemics is a more cost-effective strategy than treatment. In addition, due to developments in the field of molecular epidemiology, improved management of disease is now possible. There is a great need in the market for more user-friendly vaccines that are safer, more heat-stable, confer lifelong protection and are also cost-effective. Improved delivery systems for vaccines as well as more effective adjuvants are also required to achieve this. Much effort is being expended at present on the generation of heat-stable vaccines, for example against Newcastle disease, a devastating disease of chickens especially in developing countries.

The identification of specific genes of microbial and viral pathogens that encode for immunogenic protein antigens (proteins) is an important goal for the development of improved vaccines. One approach is to identify the antigens responsible for stimulating the formation of an antibody response after infection, then identifying and isolating the responsible genes and using these to produce recombinant or subunit vaccines. The increasing presence on the market of such vaccines for human use (e.g. the hepatitis B recombinant vaccine) indicates that once current problems are resolved, the genomic approach to vaccine development will dominate the market. Although a recombinant vaccine for rabies has been successfully used in France to eradicate fox rabies, no recombinant vaccine has yet reached the veterinary market in the developing world. A heat-stable chicken-specific poxvirus recombinant vaccine, carrying the gene responsible for conferring protection against Newcastle disease, is presently being investigated for its application in developing countries.

L. Gene Therapy

The most futuristic application of biotechnology is probably gene therapy. There are many exciting possibilities, but so far only a few experimental attempts to replace or repair defective human genes have been reported. Further experimentation in animals will probably precede the application in man. It is envisaged that inter-gene and intra-gene manipulations will play the predominant role in this field. The feasibility of gene therapy and its impact will be driven by its uniqueness and its potential for use as in an only option scenario. For most situations, however, the biotechnological revolution will be driven by the need to have better and safer solutions to combating diseases, and for improving the livelihoods of people. It is foreseen that biotechnology will have a major impact on market trends in the future. Analysts believe that the first area to benefit from these developments will be continued diagnostic applications, while market opportunities for therapeutic applications using gene therapy is probably still some way off.

ANNEX VI: RADIOISOTOPE AND RADIATION TECHNOLOGY

A. Introduction

A large variety of nuclear techniques are available for industrial, environmental, medical and research applications. Radiation and isotopic technology, such as gamma irradiation, electron beam or ion beam, as well as nucleonic gauges, radiotracers and sealed sources, non-destructive testing and nuclear analytical techniques are used for process control, material modifications, to reduce harmful industrial emissions, to reprocess waste streams and for sterilization of medical products and wastewater treatment. Non-destructive evaluation of welds, castings, assembled machinery and ceramics help to make industrial processes safer and more cost-effective. Radiotracers, sealed sources and nucleonic gauges are used for natural resource exploration in the oil industry, in mineral processing and waste water treatment plants. The application of these nuclear techniques has considerable economic and environmental impact as they are introduced in developing countries.

B. Radioisotopes

Radioisotopes make important contributions in several sectors of economic significance including medicine, food processing, industry, agriculture, structural safety and research. They are generally produced in research reactors or cyclotrons. More than 150 different radioisotopes in different forms are in use for various applications.

It has been observed that the consumption of isotopes in a country depends on the level of its economic development and industrialization: the more advanced, the more the consumption. However, the pattern of use is similar in all countries. The medical field accounts for the majority of the applications, followed by industry and research. The potential for expansion of radioisotope applications is, however, very large.

B.1. Current Status of Radioisotope Production

B.1.1. Radioisotopes for medicine

Radioisotopes in medicine are used either in liquid form, called radiopharmaceuticals, for diagnosis and therapy or as a solid sealed source for therapy, mainly for cancer. Radioisotopes also find extensive applications in *in vitro* diagnosis, the most important being in immunoassays.

Radiopharmaceuticals are used mainly for diagnostic imaging studies. However, therapeutic applications have shown a substantial growth in the last few years. The radioisotope ^{99m}Tc is used in more than 70% of the diagnostic imaging studies for assessing the dynamic functions of the various organs of the body as well as for the localization of infections. About 20% of medical applications use radioisotopes such as ^{201}Tl, ^{111}In, ^{67}Ga, ^{123}I, ^{81m}Kr, ^{131}I and ^{133}Xe. The use of the cyclotron-produced long-lived isotope ^{201}Tl for cardiac studies is also widespread.

The use of radioisotopes for Positron Emission Tomography (PET) studies is showing a faster growth rate. ^{18}F-fluoro deoxy glucose (^{18}FDG) accounts for more than 90% of PET imaging with the remaining 10% being accounted for by ^{11}C, ^{13}N and ^{15}O based radiopharmaceuticals. Interest in setting up medical cyclotrons and PET facilities has grown in many developing countries in recent years.

Radiopharmaceuticals based on ^{131}I have a primary role in the treatment of hyperthyroidism and thyroid cancer. The treatments of certain other cancers, arthritis and palliation of bone pain due to secondary cancer using radioisotopes show a substantial growth. ^{131}I, ^{32}P, ^{153}Sm, ^{90}Y and ^{186}Re are the major isotopes used in therapy. The annual turnover in this area is more than $30 million and is growing at the rate of 10% per annum.

Radioactive sealed sources are widely used for teletherapy and brachytherapy of cancer. About 1500 teletherapy machines using the radioisotope ^{60}Co are estimated to be in use worldwide. The main radioisotopes used in brachytherapy are ^{192}Ir, ^{137}Cs, ^{125}I, ^{198}Au, ^{106}Ru and ^{103}Pd. About 3000 brachytherapy centres are estimated to be in operation worldwide. High dose rate sources using ^{192}Ir are becoming increasingly popular. These use high specific activity ^{192}Ir sources, which are encapsulated by precision technology using advanced laser welding machines. The implantation of tiny sources of ^{125}I for ocular and prostate cancer is also being tried. The treatment of prostate cancer using ^{103}Pd has become very successful. The production of these sources requires remote fabrication including encapsulation by remote welding procedures.

B.1.2. Radioisotopes for industry

Radioisotopes are used for nucleonic control systems, radiation processing, non-destructive testing (NDT) and in radiotracer studies. Sealed sources of ^{137}Cs, ^{60}Co, ^{241}Am, ^{85}Kr, ^{147}Pm, ^{90}Sr/^{90}Y, ^{204}Tl, ^{252}Cf, ^{63}Ni, ^{55}Fe, ^{109}Cd, ^{57}Co and ^{241}Am-Be neutron source are used in nucleonic control systems. ^{60}Co in the form of high intensity sources is the main isotope used for radiation processing. ^{192}Ir sources are used in more than 90% of gamma radiography devices. ^{169}Yb and ^{75}Se sources are other radioisotopes used in NDT. A large number of isotopes in various chemical forms are used as tracers in industry.

B.2. Future Trends

Radioisotopes will continue to play an important role in national development. With many techniques having an important bearing on either industrial activity or health care, the sustainability of radioisotope supply or 'isotope security' continues to be a major cause of concern in view of the decrease in the number of operating research reactors worldwide and the difficulties in transporting radioisotopes worldwide because of security concerns.

The radionuclides in demand in regular medical diagnosis will continue to be ^{99m}Tc, ^{131}I, ^{201}Tl, ^{111}In, ^{123}I and ^{18}F. A substantial part of the use of ^{201}Tl for cardiac studies is likely to be carried out with ^{99m}Tc radiopharmaceuticals because of cost advantage and ready availability. The use of ^{99m}Tc generators, the technology of which is well standardized, is expected to increase significantly due to the establishment of an increased number of nuclear medicine centres in both developing and developed countries. Cold kits for the formulation of ^{99m}Tc radiopharmaceuticals for different imaging studies will be expanded, and new ^{99m}Tc radiopharmaceuticals based on peptides and other bio-molecules will be added.

The use of ^{18}FDG will increase because of better refined chemistry, starting from the production of the radioisotope through to the preparation of the radiopharmaceuticals and final quality assurance before product delivery. With ready availability of ^{18}F in several centres, further research and development of ^{18}F labelled molecules for various applications is expected to increase. Long-lived PET tracers i.e. ^{124}I and ^{76}Br are under development for studying slow processes such as monitoring gene therapy. ^{123}I production via ^{123}Xe gas target would become more widespread and economical, and may emerge as another widely used diagnostic isotope. ^{68}Ge-^{68}Ga generators are likely to see an increase in demand for use in PET where cyclotrons are not available.

Centralized production and distribution of ^{99m}Tc radiopharmaceuticals and ^{18}FDG are expected to evolve from current, predominantly hospital-based production because of increased regulatory concerns and good manufacturing practice requirements. Even though ^{99}Mo production might continue to be dominated by two or three large producers, widespread use of ^{99m}Tc coupled with the logistics of supplies and the reluctance of airlines to carry radioactive material could generate a need for many small-scale producers of fission ^{99}Mo serving regional needs.

There will be considerable interest in therapy using radiopharmaceuticals, and the range of isotopes and their products in regular use are expected to expand significantly. Refined technologies for both ^{90}Y and ^{188}Re generators will be available. Because of the similarity in the chemistry of ^{99m}Tc and ^{188}Re, research is being vigorously pursued into the development of new radiopharmaceuticals, based on peptides, and into other target specific biomolecules labelled with them, for diagnosis followed by therapy. The availability of ^{188}Re in sufficient quantities will be a major problem due to the limited availability of high flux reactors for its production.

The use of ^{90}Y radiopharmaceuticals for the treatment of cancer has shown a considerable increase. The use of ^{90}Y is advantageous because the parent radionuclide ^{90}Sr is available in large quantities from nuclear waste in fuel reprocessing programmes. The recovery of ^{90}Sr followed by large-scale centralized separation of ^{90}Y or preparation of ready-to-use radionuclide generators could become a major radiochemistry programme in other countries that have fuel reprocessing facilities. Several ^{90}Y based radiopharmaceuticals for cancer therapy and treatment of arthritis are at present in the clinical trial stage but their widespread application in the near future is envisaged.

The use of many beta particle emitting isotopes, including ^{177}Lu, ^{166}Ho, ^{153}Sm, ^{165}Dy and ^{186}Re, for therapy could increase by taking advantage of local reactor production. ^{177}Lu offers a particular advantage, as this isotope can be prepared with very high specific activity and in large quantities, even in reactors having moderate flux. The near future could see large-scale deployment of ^{177}Lu in cancer therapy. ^{124}I and ^{103}Pd from cyclotrons will also be increasingly used for therapy. ^{125}I and ^{103}Pd seed production technology for brachytherapy applications will be in demand in many countries.

C. Radiation Technology for Clean and Safe Industry

C.1. Radiation Processing

As well as economic factors, radiation and radioisotope applications have great impact on different aspects of social and industrial development, for example:

- Human health (radiation sterilization of medical products, blood and transplanting grafts irradiation);
- Environment protection (electron beam flue gas and wastewater treatment, gamma rays sludge hygienization);
- Clean and safe industry (radiotracer leakage testing and Non Destructive Testing (NDT) of installations, pipes, tanks);
- Quality system enhancement (nuclear analytical techniques, NDT);
- Process optimization (radiotracers and Nucleonic Control Systems);
- Raw materials exploration and exploitation (on-line processing, borehole logging); and
- Homeland security (cargo inspections, governmental mail irradiation).

Radiation and radioisotope applications make a large contribution to economies. The economical scale of industrial applications of radiation and isotopes in the USA and Japan, based on earlier studies, is given in Table VI.1.

TABLE VI.1.

ITEM	ECONOMIC SCALE (billions$)	
	USA	JAPAN
1. Sterilized medical supplies	4.8	2.3
2. Semiconductors	37.2	28.4
3. Radiographic testing (NDT)	0.65	0.26
4. Radiation cured radial tyres	13.5	8.4
Total	56.15	39.36

The number of industrial gamma irradiators, working on a service basis or installed on-line worldwide exceeds 160, of which 65 units are operational in developing countries. More than 20% of these gamma irradiators have activities over 1 MCi of ^{60}Co.

The total number of electron beam accelerators installed exceeds 13 000, with close to 1200 units being used for radiation processing. New environmental applications demand the development of high power, reliable accelerators. The most powerful radiation processing facility, applying electron accelerators over 1 MW total power, has been constructed for power-plant-emitted flue-gases purification in Poland.

The concept of electron beam to X-ray conversion is a new technological approach for constructing powerful X-ray machines, with R&D under way in some pilot units. A breakthrough in the technology is expected after work on a high energy unit (up to 700 kW), which is already under test in Belgium.

Chemical or material engineering mostly applies high temperature and/or high pressure processes for material synthesis/modification. Often a catalyst is required to speed up the reaction. Radiation, however, is a unique source of energy that can initiate chemical reactions at any temperature, including ambient, under any pressure and in any phase (gas, liquid or solid) without use of catalysts.

Polymers are often irradiated, either for modification or as components of radiation sterilized medical products. Therefore, changes in their structure may be beneficial or undesirable. Polymer R&D is broad and most developments are foreseen in this area.

Another possible application is the processing of natural polymers. Cellulose materials for the pharmaceutical and cosmetics industry have already been fabricated.

Radiation sterilization is a well-established technique, and multi-technique services employing radiation and heat have emerged recently. A new application of these techniques is decontamination of mail against biological contaminants, such as anthrax.

Some radiation processes have promising applications for environment conservation. The plant for liquid sludge hygienization using a ^{60}Co gamma source has been in operation in India since 1991.

A pilot plant for dye factory wastewater treatment equipped with an electron accelerator has been constructed in South Korea, and an industrial project aiming to treat 10 000 cubic meters of effluent per day is in progress.

Electron beam flue gas treatment plants are operating in coal-fired plants in China and Poland purifying flue gases from 100 MW(e) units. High efficiency of SO_x and NO_x removal has been achieved with a by-product of high quality fertilizer. The other possible application of the technology is Volatile Organic Compound and Polycyclic Hydrocarbon treatment, e.g. in municipal waste incinerator plants and flue gas purification units. The advantage of this technology over conventional ones has been clearly demonstrated, both from a technical and economic point of view.

Conservation of archaeological artefacts and art objects by radiation (gamma rays or electron beam) appears to have prospects. Ongoing studies on the application of radiation for consolidation revealed that lacquer, textiles, paper, objects made of wood, stone and gypsum can be considered for conservation purposes.

C.2. Radiotracers and Sealed Source Applications

Radioisotopes (^{3}H, ^{82}Br, ^{99m}Tc, ^{140}La, ^{24}Na, ^{131}I) are applied as radiotracers in industry and the environment. Oil fields and refineries, chemical and metallurgical industries and wastewater purification installations are the particular users.

Radioisotope techniques (radiotracers, gamma scanning, tomography and single particle tracking) are extensively used to identify and quantify multiphase reactors (phase hold-up distributions, velocity and mixing patterns). Multiphase reactor technology is the basis for petroleum refining, synthesis gas conversion to fuels and chemicals, bulk commodity chemicals production, manufacture of special chemicals and polymers, and the conversion of undesired products into recyclable materials. Quantification of the reactor performance requires a description of: (i) kinetics on a molecular scale; (ii) the effect of transport on kinetics on a single eddy or single catalyst particle scale; and (iii) the phase distribution, flow pattern and mixing in the reactor on the reactor scale. It is critical to understand and predict at what rates each reactant can be supplied to the micro scale and how changes in reactor size or operating conditions affect these rates of supply. While progress has been made in understanding fundamental reaction mechanisms and in computing from first principles the effect of mass transfer on the reaction rate locally, the description of the reactor scale flow pattern and mixing is in general primitive and rests on the assumption of ideal flow patterns. Radioisotope techniques help optimizing multiphase reactors saving hundreds of million of US dollars annually worldwide.

Information gained from interwell use of tracers in oil fields is indispensable for the evaluation and optimization of oil field performance. It is possible to make qualitative or semi-quantitative evaluations, as was the case of a reservoir in Colombia, which is naturally heavily compartmentalized. Information about fluid flow across faults, and therefore the effect of water injection could only be studied by the use of tracers. Several wells were uniquely labelled, and the exercise showed that there was an unexpectedly good communication across a fault that originally was a suspected barrier.

D. Nuclear Analytical Techniques

Nuclear analytical techniques play an important role in the certification of element content in a variety of materials. Particularly in international trade, for example in food, legal limits have to be observed and analytical results need to be based on mutual recognition, which is obtained if laboratories work according to internationally accepted quality standards such as the ISO 17025. National accreditation following the installation of a concise quality system assures nuclear analytical laboratories' superior performance compared to conventional analysis.

New trends in nuclear applications can be seen in the development of robust, automated and portable instruments, which can be used under laboratory as well as under field conditions. Flexible X-ray fluorescence instruments have been used for non-destructive analysis of art objects. Portable neutron sources of variable strength are developed for field applications of prompt gamma neutron activation analysis enabling fast and non-destructive element screening of, e.g., unknown packages suspected of illicit trafficking of nuclear materials. There are different nuclear analytical techniques applied for package inspection depending on the size and content of the packages. Dual energy X-ray absorption analysers are most familiar in their use as on-line security devices screening baggage at airports.

Long lived radionuclides and stable isotopes are increasingly used to study metabolic effects of essential and toxic elements in plants, animals and the human body. Monte Carlo simulations of neutrons and gamma rays enable the design of new irradiation and counting devices optimized for a particular application.

Nuclear techniques also serve in preserving human cultural heritage. Neutron Activation Analysis is very sensitive multi-elemental analysis that allows identification of art objects. Coins and other metallic artefacts, stones, pottery and ceramics have all been subjected to trace element fingerprinting to distinguish originals from fakes. Neutron activation analysis has been successfully demonstrated as a technique to add valuable information to the interpretation of archaeological problems.

REFERENCES

[1] Ananthakrishnan, M. 2003, Radiotracers–Production and Application, Proceedings of BRNS-DAE National Symposium on Nuclear and Radiochemistry, BARC, Mumbai, India, 57.

[2] Chapiro, A., 2002, Polymer irradiation: past-present and future. Rad.Phys.Chem. 63(3-6), 207-209

[3] Cleland, M.R., Parks, L.A., 2003a, Medium and high-energy electron beam radiation processing equipment for commercial applications. Nucl.Instrum.Methods in Phys.Res.Sec.B, 208, 74-89.

[4] Cleland, M.R., Parks, L.A., Cheng, S., 2003b, Application for radiation processing of materials. Nucl.Instrum.Methods in Phys.Res.Sec.B, 208, 66-73.

[5] Drobny, J.G., 2003, Radiation Technology for Polymers. CRC Press, New York.

[6] Druker, M.P., 1994, Ethical responsibilities of environmental engineers. In: Remediation of Hazardous Waste Contaminated Soils. Eds.Wyse, D.L., Trantolo, D. J., Marcel Dekker Inc., New York.

[7] Fairand, B.P., 2002, Radiation Sterilization for Health Care Products – X-Ray, Gamma and Electron Beam. CRC Press, New York.

[8] IAEA, 2003, Directory of Commercial Radiation Processing Facilities in Member States. Vienna, Austria, in press.

[9] IAEA, 2002, Radioisotope Applications for Troubleshooting and Optimising Industrial Processes, Vienna.

[10] IAEA, 2003, Report from a technical meeting; emerging applications of radiation processing for 21st century. Vienna, Austria.

[11] IAEA, 2003, Tracer Applications in Oil Field Applications, Vienna

[12] Morrissey, R.F., Herring, C.M., 2002, Radiation sterilization: past, present and future. Rad. Phys. Chem. 63 (3-6), 217-221.

[13] Nordion, 2003, Supplies of Contract Irradiation Services. Ottawa, Canada.

[14] Tagawa, S., et al. Economic scale of utilization of radiation (I): Industry. Comparison between Japan and USA, Journal of Nuclear Science and Technology, Vol. 39, No. 9, pp. 1002-1007, September 2002. A publication of the Atomic Energy Society of Japan.

[15] IAEA, Technical Report Series No. 416. Nuclear Techniques in Archaeological Investigations, Vienna, August 2003

ANNEX VII: DESALINATION

A. Introduction

Seventy percent of the planet is covered with water, but only 2.5% of that is freshwater. Nearly 70% of this freshwater is frozen in the icecaps of Antarctica and Greenland. Most of the rest is in the form of soil moisture or in deep inaccessible aquifers (Helmer, 1997), or comes in the form of monsoons and floods that are difficult to contain and exploit. Less than 0.08% of the world's water is thus readily accessible for direct human use, and even that is very unevenly distributed.

Currently about 2.3 billion people live in water-stressed areas and among them 1.7 billion live in water-scarce areas, where the water availability per person is less than 1000 m^3/year. Statistics show that by 2025 the number of people suffering from water stress or scarcity could swell to 3.5 billion, with 2.4 billion expected to live in water-scarce regions. Water scarcity is a global issue, and every year new countries are affected by growing water problems.

Better water conservation, water management, pollution control and water reclamation are all part of the solution to projected water stress, as are new sources of fresh water, including the desalination of seawater. Desalination technologies have been well established since the mid-20th century and widely deployed in the Middle East and North Africa. The contracted capacity of desalination plants has increased steadily since 1965 and is now about

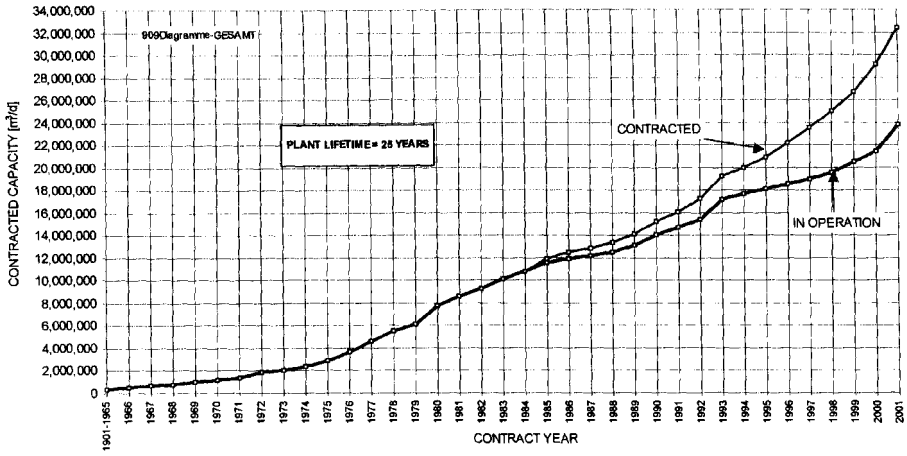

FIG. VII.1. Cumulative worldwide desalination capacity. The top line shows total operating and contracted capacity. The bottom line shows just operating capacity.

32.4 million m^3/d worldwide, as shown in Figure VII.1 (Wangnik, 2002). This corresponds to approximately 15 233 units with an average capacity of 2000 m^3/d.

Large scale commercially available desalination processes can generally be classified into two categories: (a) distillation processes that require mainly heat plus some electricity for ancillary equipment, and (b) membrane processes that require only electricity. In the first category (distillation) there are two major processes: multi-stage flash (MSF) and multi-effect distillation (MED). Seawater is heated in both processes, the steam that evaporates is condensed and collected as freshwater, and the residual brine is discharged. In the second category (membranes) is the reverse osmosis process (RO), in which pure water passes from the high pressure seawater side of a semi-permeable membrane to the low pressure freshwater permeate side. The pressure differential must be high enough to overcome the natural tendency for water to move from the low concentration freshwater side of a membrane to the high concentration seawater side in order to balance osmotic pressures. Energy consumption, including energy for seawater pumps and water pre-treatment, is lowest in the RO process. Energy inputs, whether in the form of heat or electricity have historically been produced largely by conventional fossil fuels.

B. The Role of Nuclear Power

Japan now has over 125 reactor-years of nuclear powered desalination experience as shown in Table VII.1. Kazakhstan had accumulated 26 reactor-years before shutting down the Aktau fast reactor at the end of its lifetime in 1999. As shown in the table, the experience gained with the Aktau reactor is unique as its desalination capacity was orders of magnitude higher than at other facilities.

Looking to the future, there are two main reasons for focusing on expanding nuclear power's contribution to both heat and electricity for desalination. One is the expanding demand for freshwater as described above, and the second is the increasing concern about greenhouse gas (GHG) emissions and pollution from fossil fuels. There is also now a growing emphasis on small and medium size reactors, which may prove important for desalination because the countries most in need of freshwater often have limited industrial infrastructures and electricity grids. The size of the grid limits the possibilities for integrating a co-generating nuclear power plant into the grid to supply the electricity, in addition to meeting the energy requirements of a desalination plant. The largest power unit that can be integrated into an electricity grid is about 10-20% of the grid capacity.

TABLE VII.1. EXPERIENCE WITH NUCLEAR DESALINATION (IAEA, 1998, 2000; WANGNICK, 2000)

Country	Unit name	Location	Phase	Start of power operation	Power, MWe net	Water Capacity, m^3/day	Desal. Process
Japan	Ikata-1	Ehime	Comm.	1977	538	2000	MSF
	Ikata-2	Ehime	Comm.	1982	538		
	Ikata-3	Ehime	Comm.	1994	846	2000	RO
	Ohi-1	Fukui	Comm.	1979	1120	6500	MSF x 2 MDE x 1 RO x 2
	Ohi-2	Fukui	Comm.	1979	1120	MSF+	
	Ohi-3	Fukui	Comm.	1991	1127	MDE=3900	
	Ohi-4	Fukui	Comm.	1993	1127	RO=2600	
	Genkai-3	Saga	Comm.	1994	1127	1000	MED
	Genkai-4	Saga	Comm.	1997	1127		
	Takahama-3	Fukui	Comm.	1985	830	1000	MED
	Takahama-4	Fukui	Comm.	1985	830		
	Kashiwazaki-Kariwa 1	Niigata	Comm.	1985	1067	1000	MSF
Kazakhstan	BN-350	Aktau	Comm.	1973	70	120 000	MED/ MSF

The High Temperature Gas cooled Reactor (HTGR) design, one of the leading reactor concepts currently under consideration for future nuclear power plant deployment, is one of the candidate reactor designs well suited for such process heat applications. Traditionally emphasis has been on HTGR suitability for high temperature applications such as hydrogen production, but its potential for low temperature applications such as nuclear desalination is attracting interest with the provision of virtually cost-free waste heat at the cycle sink boundary, and at the desired range of temperatures (100-120 ºC) needed for desalination. Since a good proportion of the total production cost of seawater desalination - in the range of 30% to 50% - is attributed to energy cost, the potential exists for a significant reduction in the cost of freshwater production using an HTGR in co-generation mode, boosting thermal utilization efficiency and promising a safe, clean and economically competitive heat source.

C. Current Developments

Table VII.2 summarizes past experience as well as current developments and plans for nuclear powered desalination. Most of the technologies in Table VII.2 are land-based, but the table also includes a Russian initiative for barge-mounted floating desalination plants. Floating desalination plants could be especially attractive for responding to temporary demands for potable water.

TABLE VII.2. REACTOR TYPES AND DESALINATION PROCESSES

Reactor Type	Location	Desalination Process	Status
LMFR	Kazakhstan (Aktau)	MED, MSF	in service till 1999
PWRs	Japan (Ohi, Takahama, Ikata, Genkai)	MED, MSF, RO	in service with operating experience of over 100 reactor-years.
	Rep. of Korea, Argentina, etc.	MED, RO	under design
	Russia	MED, RO	under design (floating unit)
BWR	Japan (Kashiwazaki)	MSF	never in service following testing in 1980s, due to alternative freshwater sources; dismantled in 1999.
PHWR	India (Kalpakkam)	MSF/RO	being connected
	Canada	RO (preheat)	under design
	Pakistan (KANUPP)	MED	under design
NHR	China	MED	under design
HTGR	South Africa, France, The Netherlands	MED, MSF, RO	under consideration

The following paragraphs provide additional detail on the new developments listed in Table VII.2:

- Argentina has identified a site for its small reactor (CAREM), which could be used for desalination. Depending on financing, construction could begin in the near future.
- Canada has embarked on a three-year project to validate its innovative reverse osmosis (RO) system design concepts.
- China is proceeding with several conceptual designs of nuclear desalination for coastal Chinese cities.

- France has a joint European study on reactor development for nuclear desalination (the EURODESAL Project).
- Egypt has completed a feasibility study for a nuclear co-generation plant (electricity and water) at El-Dabaa.
- India is building a demonstration plant at Kalpakkam using a 6300 m^3/d hybrid desalination system (MSF-RO) connected to an existing PHWR. Civil engineering and electrical work is completed, and India expects to commission the plant in early 2004.
- The Republic of Korea is proceeding with its SMART (System-integrated Modular Advanced Reactor) concept. The basic design was completed in 2002, and a six-year project for the construction of a one-fifth scale pilot plant SMART-P was started to verify the integral performance of the SMART system and nuclear desalination. The project is designed to produce 40 000 m^3/d of potable water.
- Morocco, in June 2000, halted a demonstration project at Tan-Tan originally intended to produce 8000 m^3/d of potable water using an NHR-10 of Chinese design. Possible next steps are being studied.
- Pakistan is considering coupling a MED thermal desalination plant of 4800 m^3/d capacity with the existing PHWR at KANUPP.
- In Russia, design work continues for a floating nuclear heat and power plant based on marine reactor technologies. Construction of the first plant is scheduled to begin in 2005 or 2006 in the northern European part of Russia. Plans call for a floating unit with two KLT-40S reactors to be used as the power source for nuclear desalination facilities. Manufacturing of major components started in 2000.
- Tunisia has undertaken several studies to select a suitable desalination process and to identify what process could be coupled to a nuclear reactor. Two possible desalination sites have been identified in the southeast part of the country for further study.
- The USA will include in its Generation IV roadmap initiative a detailed discussion of potential nuclear energy products in recognition of the important role that future nuclear energy systems can play in producing freshwater.
- Further R&D activities are also underway in Indonesia and Saudi Arabia. In addition, interest has been expressed by Brazil, Iran, Iraq, Italy, Jordan, Lebanon, Libya, Philippines and Syria in the potential for nuclear desalination in their countries or regions.

D. Economics

The worldwide use of desalination is still negligible compared to the demand for freshwater. To become a noticeable (and quantifiable) market for nuclear energy, desalination needs to compete successfully with alternative means of increasing freshwater supply. For nuclear desalination to be attractive in any given country, two factors must be in place simultaneously: a lack of water and the ability to use nuclear energy for desalination. In most regions, only one of the two is present. Both are present, for example, in China, India, the Republic of Korea and Pakistan. These regions already account for almost half the world's population, and thus represent a potential long-term market for nuclear desalination. The market will expand further to the extent that regions with high projected water needs, such as the Middle East and North Africa, increase their nuclear expertise and capabilities.

REFERENCES

[1] Gowin *et al*. (1999), *Nuclear Seawater Desalination - IAEA Activities and Economic Evaluation*, IDA World Congress, San Diego, USA; Desalination Economic Evaluation Program (DEEP) – User's Manual Series No. 14, 2000.

[2] Helmer (1997), *Water Demand and Supply*, International Symposium on Seawater Desalination with Nuclear Energy, Taejon, Republic of Korea

[3] IAEA (1990), Use of Nuclear Reactors for Seawater Desalination, IAEA-TECDOC-574, 1990.

[4] IAEA (1992), Technical and Economic Evaluation of Potable Water Production through Desalination of Seawater by Using Nuclear Energy and Other Means, IAEA-TECDOC-666, 1992.

[5] IAEA (1996a), Options Identification Programme for Demonstration of Nuclear Desalination, IAEA-TECDOC-898, 1996.

[6] IAEA (1996b), Potential for Nuclear Desalination as a Source of Low Cost Potable Water in North Africa, IAEA-TECDOC-917, 1996.

[7] IAEA (1997a), Methodology for the Economic Evaluation of Cogeneration/ Desalination Options: A User's Manual, IAEA Computer Manual Series No. 12, 1997.

[8] IAEA (1997b), Thermodynamic and Economic Evaluation of Co-production Plants for Electricity and Potable Water, IAEA-TECDOC-942, 1997.

[9] IAEA (1998), Nuclear heat applications: Design aspects and operating experience, IAEA-TECDOC-1056, 1998.

[10] IAEA (2000), Introduction of nuclear desalination: a Guidebook, IAEA-Technical Report Series No. 400, 2000.

[11] IAEA (2002), Design concepts of nuclear desalination plants, IAEA TECDOC-1326, 2002.

[12] Wangnick, K. (2002), *IDA Worldwide Desalting Plants Inventory Report No.17*, Wangnick Consulting GmbH and the International Desalination Association (IDA), Vienna, July, 2002.

[13] World Water Council (2000), *The World Water Vision*, the Second World Water Forum, The Hague, The Netherlands.

[14] World Water Forum (2000), "World Water Vision Commission Report: A Water Secure World," World Water Forum, The Hague, Netherlands, 17-22 March 2000.

[15] World Water Forum (2000), "World Water Vision, Making Water Everybody's Business," World Water Forum, The Hague, Netherlands, 17–22 March 2000.

ANNEX VIII: THE SOCIO-ECONOMICS OF NUCLEAR APPLICATIONS: A PERSPECTIVE

A. Abstract

The mandate of the International Atomic Energy Agency is to "accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" and in so doing it does more than simply facilitate progress in nuclear sciences. However, the potential contribution of even the most novel or sophisticated nuclear technique should be compared and judged against its conventional, non-nuclear competitors. Cost, reliability, safety, simplicity and sustainability are important elements for the basis of decisions by governments, private companies, universities, and citizens/ consumers. Reliable information is needed to assist in making choices that in the nuclear area are often shaped by perceptions and misperceptions about risk.

Assessments of the benefits created by the peaceful uses of the atom are needed as well as a clear understanding of risks to better understand the present impact of nuclear applications and to assist in making the best use of established and emerging nuclear applications. Different approaches are being developed to quantify the nuclear activities discussed. These assessments can, even at the present stage, provide valuable insights for the development of realistic visions and efficient planning and implementation schemes.

B. Introduction

The IAEA has an extensive and varied programme to enhance existing nuclear techniques, or to assist in developing new ones, and to transfer those providing tangible benefits to its developing Member States. 'Atomic energy' makes important contributions in many areas, which affect the every day lives of billions of people around the globe. Nuclear techniques make our food safer and more abundant, help prevent, diagnose, and cure disease, optimize sustainable water use, and protect the environment. Nuclear techniques have made significant contributions and have the potential to contribute much more in key areas of concern to the international community as identified in the Agenda 21 Action Plan, the Millennium Declaration, and the World Summit on Sustainable Development (WSSD) in Johannesburg 2002, particularly the WEHAB issues of Water, Energy, Health, Agriculture and Bio-diversity.

It is important to understand the ways in which the contributions of nuclear techniques have been made and to be able to quantify them. They could be evaluated solely in terms of their economic impact, but consideration also needs to be given to their overall impact, taking into account environmental and other considerations. Indeed, a healthy and sustainable environment was identified as a pre-requisite for success in achieving WSSD goals.

The Agency's activities need to be assessed in terms of how they contribute to human welfare, both social and economic, and importantly, their likely impact on future generations should be understood in terms of society's resources, i.e. its institutions, its public knowledge, human capital, manufactured capital and natural capital. In an increasingly globalized world, national or regional contributions may also benefit a global community and not just a single society. In comparing with other options for socio-economic development, the sustainability of newly introduced processes needs special consideration.

C. Assessing the Impact of Nuclear Techniques

Nuclear techniques are used everywhere to measure, manage, and affect daily lives. Precise, isotopic measurements are used to understand human beings and their environment, for example, human energy requirements, pollution monitoring or global climate change. Radiation measurements improve industrial quality control and help diagnose disease. Radiation itself cures cancers, creates new plant varieties, and eliminates insect pests. In the power sector, nuclear fission produces about 16% of the world's electricity. The total impact of all contributions is large, but needs better assessment techniques to determine the precise values of the nuclear contribution.

For some activities the nuclear contribution is self evident and dominant. Nuclear energy production, for example, includes nuclear fuel cycle activities performed by professionals with nuclear expertise, regulated by nuclear authorities, and relying on a highly specialized industrial and knowledge pool. The totality of impacts is far-reaching, affecting for example, education, employment, energy supplies, local and national economies, environments and global climate.

Diagnostic radiology, nuclear medicine, and radiation therapy services also depend on a specialized infrastructure and knowledge pool. Doctors and technicians perform billions of procedures per year worldwide that depend on a stable supply of isotopes or the safe use of radiopharmaceuticals and radiation. Their total 'market value' is very large, but other aspects of their

impacts are difficult to quantify, such as the evaluation of the contribution of a nuclear diagnostic procedure that is a prerequisite to a surgical procedure that leads to the prolongation of a patient's life as a person, or as a parent, a wage earner or a retiree.

In other cases, a key nuclear step may make only a small contribution in cost terms to a discrete end product. In Japan, for example the production of almost all radial tyres with a market value of $9 billion/year involves radiation treatment to optimize cross-linking of rubber molecules.

A third group of nuclear applications in plant breeding, food security, pest control, and water management plays an important role in national and regional enterprises providing the essentials of life – adequate supplies of safe food and water. The nuclear contribution may be small, but it is often unique and may be indispensable. The impacts can be enormous and returns on investment large, even if they are difficult to measure. The successful introduction of a hardier plant variety may profoundly change large agricultural systems. The control/eradication of an insect pest can free farmers in least developed countries from crippling constraints or empower them to overcome sanitary barriers to international trade. Changes in national economies can be significant.

The following examples from the fields of energy, agriculture, health, water, and industry exemplify specific aspects and develop some elements that can be used to quantify the impact of nuclear and isotopic technologies and techniques.

D. Energy

In 2003, 439 nuclear power plants in 30 countries produced about 16% of the world's electricity. The nuclear share of electricity produced exceeds 75% in France, 30% in Japan, and 20% in the United States, and thus the socio-economic impact of nuclear power production varies from country to country. At an economic level, the impact can be assessed by looking at the market value of the produced electricity. For Japan and the United States, this is estimated for 1997 at $47 billion and $39 billion respectively, over ½% of GDP in both countries[22]. In France, where the fraction of electricity produced by nuclear is considerably higher, this figure is about 1.5%. (These estimates are based on retail prices of electricity. Subtracting the transmission and distri-

[22] Tamikazu Kume, Etsuo Amano, Tomoko M. Nakanishi, and Mitsuo Chino, Journal of Nuclear Science and Technology, Vol. 39, No. 10, pp. 1106-1113, October 2002

bution costs – non-nuclear components – would reduce the nuclear contribution by about twofold.) Societal and environmental factors also have to be taken into account. Many are indirect and include value judgments and perception. Not all are included in electricity market prices from different fuels. In looking at alternatives, some factors are easily quantifiable, e.g., emissions of greenhouse gases or particulates, but not their assessment for impact on health and climate. For nuclear, the costs of decommissioning nuclear plants or the costs of long-term storage of nuclear waste can be estimated, but potential costs from accidents are difficult to factor into the equations. Funds for decommissioning and waste disposal are sometimes included in the cost of nuclear production, but the cost of non-sustainable fossil fuel burning, operated on the 'dilute and disperse' principle, remains unaccounted for. Therefore, comparative exercises are complex in nature and prone to disagreements (Helsinki 1991[23]). However, of all areas of nuclear application, nuclear energy production has been assessed in most detail, and the social or economic benefits quantified from the various perspectives taken by the researchers. Lessons learned from the analysis techniques can be used or modified for other fields of nuclear applications.

E. Food and Agriculture

Major nuclear applications in food and agriculture are crop mutation breeding, pest control and food irradiation. Research in this area also relies heavily on nuclear techniques, e.g. for soil erosion, the water cycle, analyses of residues and environmental impact assessment.

For centuries, farmers and plant breeders have sought to improve plant varieties. Since the 1950s, there has been a concerted effort by international agricultural research centres and national agricultural research systems to improve agriculture in developing countries through the development of new crop varieties with higher yield or increased resistance to environmental stresses such as drought, salinity or pests. Thousands of new varieties have been released and results have been impressive. Evenson and Gollin[24] estimate that today, "in the absence of international research … caloric intake per capita in the developing world would have been 13.3% to 14.4% lower, and the

[23] Chadwick M.J. et al., Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation. Key Issues Paper 3, Senior Expert Symposium on Electricity and the Environment. Helsinki, 91-141, 1991

[24] R.E. Evenson and D. Gollin, **Science**, Vol. 300, No. 5620, pp. 758-762, 2 May 2003.

proportion of children malnourished would have been from 6.1% to 7.9% higher." They conclude that "virtually all consumers in the world have benefited from lower food prices". Overall, they demonstrate that returns to consumers from the investments made in international agricultural research have been large. At the same time, cheaper products from more efficient competitors often hurt small farmers, and higher yield plants have led to increased use of fertilizers to maximize their potential. Concerns have also arisen about the sustainability of intensive agriculture and the environmental consequences of soil degradation, chemical pollution, soil salinity, and biodiversity.

One major method used in the Green Revolution is irradiation-induced mutation breeding followed by selection for desired traits. Although the role of this method in achieving global results has not been estimated, it is clear that it is large. For example, the percentage of rice areas devoted to varieties produced with the help of irradiation in 1998 was at least 28% in Thailand, 19% in Laos, and 14% in Vietnam.[25] Kume et al.[26] estimate that in Japan, plant varieties produced via radiation-induced mutations command a market share of $804 million annually. In Pakistan, 25% of the area under cotton is planted to a gamma ray induced, high yielding mutant cultivar. It is estimated that this cultivar has contributed more than $3 billion in cotton production and saved the textile industry of Pakistan when it was threatened by reduction in cotton production from insect pests.

Area wide pest control using the sterile insect technique (SIT) is well established for eradication and control of the Mediterranean fruit fly to protect citrus orchards and vineyards, and for the screwworm to protect cattle. Economic benefits per year for the United States from SIT are estimated at $1.5 billion and $1.3 billion, respectively, from the control of these insects. Protection of the environment from insecticides and preservation of biodiversity are additional benefits of this species-specific technology. The extension of SIT to the Tsetse fly, threatening both animal and human health and one of the major obstacles to African rural development, is under way with considerable Agency support and has already resulted in Zanzibar being free of this pest. As a result of this effort, farmers in Zanzibar can now take better

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[25] M. Hossain, D. Gollin, V. Canabilla, E. Cabrera, N. Johnson, G.S. Khush, and G. Mclaren, International Research and Genetic Improvement in Rice: Evidence from Asia and Latin America, in R. E. Evenson and D. Gollin (eds) (2003) *Crop Variety Improvement and Its Effect on Productivity*, CABI Publishing, Wallingford UK.

[26] Tamikazu Kume, Etsuo Amano, Tomoko M. Nakanishi, and Mitsuo Chino, *Journal of Nuclear Science and Technology*, Vol. 39, No. 10, pp 1106-1113 (October 2002).

advantage of varieties of cattle with high yields of milk and meat. The number of farmers who do so has risen significantly since 1999, as has milk production and farm output. The Agency has recently initiated a research and development program at its Seibersdorf laboratories to develop SIT for the control of malaria through area-wide suppression of mosquitoes. Considerable progress in rearing methods and gender selection are needed before field trials planned for the northern state of Sudan and French Reunion Island can be initiated.

Food irradiation has the potential to replace chemical fumigation to prevent spreading of pests in international trade and is increasingly used to secure the microbiological safety of foods such as ground meat or spices. In the United States, for example, 5% of ground beef is irradiated from a total market of 4 billion kg. Food irradiation has been declared safe by the FAO/ WHO Codex Alimentarius, but public acceptance varies considerably from country to country.

F. Health

Nuclear applications in medicine serve many aspects of modern health care, contributing significantly to prevention, diagnosis and cure. Radioactive tags in biomedical research are central to progress in genomics and proteomics. From the visualization of the bones in Ms. Roentgen's hands to modern radiology in dentistry and orthopaedics, X-rays have provided a cheap and non-invasive means to image fractures, to understand pathological processes, and to guide efficient treatment. Present day applications range from relatively inexpensive dental X-ray machines to sites with their own accelerators to

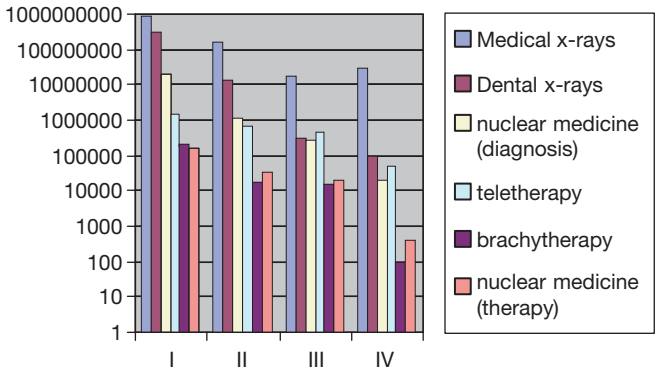

FIG. VIII.1. Rates of nuclear medicine procedures (relative) from most developed (category I) to least developed countries (category IV) - UNSCEAR 2000.

produce radioisotopes for positron emission tomography (PET) scans. Hardware investments can range from a few tens of thousands of dollars for an X-ray unit to millions of dollars or more for sophisticated nuclear imaging systems.

As can be seen in the previous chart, a strong gradient exists between advanced countries and least developed Member States where the potential of nuclear in medicine is practically untapped.

The Agency is working to help realize this potential, especially in treating cancer, whose dramatic rise across the developing world is straining already limited resources and equipment. Some 5000 radiotherapy machines are needed to help patients fight cancer, but the entire developing world has only about 2200 such machines. Experts predict a long term crisis in managing cancer, with an estimated five million new patients requiring radiation therapy every year. Providing essential equipment and training of staff to safely treat cancer patients in the developing world is of increasing importance, with socio-economic benefits potentially far outweighing costs of investments.

G. Water

Today there are more than one billion people who lack access to a steady supply of clean water. The Millennium Declaration resolved by 2015 to "halve the proportion of people who are unable to reach or afford safe drinking water" and to stop the unsustainable exploitation of groundwater. This translates into more than 300 000 additional people being provided with this basic human need every day from now to 2015. Nuclear techniques in isotope hydrology play an important role in addressing this problem. Water samples have specific isotopic fingerprints that can tell age, origin and climatic conditions, and nuclear techniques have become a basic tool to understand and manage water resources in a sustainable way. Water supplies are already scarce and will become more precious due to increasing demand from development. Agriculture is by far the biggest consumer, consuming 70% of all water withdrawals from rivers, lakes, and aquifers.[27] In Bangladesh, isotope studies have led to a new understanding of the water resources available and also contributed as well to the understanding of how arsenic enters the water table. At a cost of about $50 000, these studies have helped shape how a much larger investment in excess of $50 million is to be spent. They will have a large impact

[27] *Water for People, Water for Life*, UN World Water Development Report (2003), p. 193.

because tens of millions of people have been poisoned by arsenic in the present ground water supply system and need to find a sustainable alternative. Other methods could have been used, although they could not have provided as good an understanding of complex water systems. The value added from the isotope studies is complex because the outcomes in the field have yet to be realized, but it is certain that nuclear techniques have improved understanding of the region's hydrology and so provided value to the people of Bangladesh.

H. Industry

A broad and diverse array of nuclear applications is routinely used in industry. They include physical measurement gauges, humidity/density meters, oil well logging tools, smoke detectors, radiation processing (for example sterilization of medical supplies and curing of plastic and rubber), and use of radioactive tracers to check performance and optimize processes in a wide range of industrial plants.[28]

Although the initial nuclear inputs may have a relatively low dollar value, they often contribute in a unique fashion to much larger social or industrial enterprises. For example, radiotracer studies for a major oil company revealed that the mean residence time of water and oil in a separator column was a quarter of the design value. Subsequent modifications led to a daily increase of $600 000 per day in production.[29]

I. Frameworks

In viewing these snapshots, it is important to keep in mind the importance of the national and international frameworks within which they take place. Nuclear safety, radiation protection, food standards, etc., and the establishment and implementation of legal frameworks to control them, both national and international as appropriate, are essential and a prerequisite for sustainable nuclear applications.

It should also be noted that many nuclear applications with socio-economic benefits do not involve ionizing radiation, and because they pose no risks, are outside of nuclear or radiological regulatory controls. Stable isotopes

[28] See *Beneficial Uses and Production of Isotopes*, NEA, 1998, and its 2000 Update.

[29] IAEA's Nuclear Technology Review 2002.

in water resources and nutrition, as well as biomedical tests and improved crop varieties are important examples. Cost benefit analyses in these areas need to recognize that different, non-nuclear infrastructures are required to apply such sophisticated techniques on an area-wide basis and, if necessary, to conform to the specialized international requirements, for example, in food distribution. As public awareness grows of the potential national, regional and global impacts of nuclear and non-nuclear methods for the production and distribution of food and energy, increasing attention to the socio-economic benefit aspects will need to be paid to those particular areas where nuclear sciences and applications can provide cost effective and low-risk alternatives.

J. Perspectives

Nuclear sciences and applications are recognized as some of the core disciplines on the road to technologically advanced societies. All countries, to a greater or lesser extent, take advantage of nuclear applications, especially in health care. While utilization increases dramatically with countries' social, technological, and economic development, significant socio-economic benefits can be obtained at all levels of development, but to realize these benefits the contributions of nuclear science and applications need to be properly embedded into major economic activities such as agriculture, health, water resource management, industrial applications and energy. Accurate assessments of their costs, benefits, and risks are needed for decision makers to have correct and reliable tools for sustainable development. Currently, major benefits have accrued and remain available to both developed and developing countries, and it has also been shown that investments in the requisite technical, scientific, and regulatory infrastructure can be rewarded relatively quickly, but recognizing that some aspects may need some years to mature. All applications combined may amount to several percent or more of GNP in highly developed countries, but may be practically non-existent in least developed countries. However, the experiences of the larger economies demonstrate that there remains a large, untapped potential for nuclear sciences and applications to contribute significantly to meeting basic human needs around the world.

The transfer by the Agency of human, regulatory, technical, and scientific nuclear capabilities are important activities for socio-economic development, but need to be put into context in terms of 'value added' or of comparative cost-effectiveness with non-nuclear techniques. Assessment techniques need to be adapted to the relevant nuclear or isotopic application and studies need to define realistic boundary conditions for socio-economic impact assessments to

be meaningful. The challenges of correctly assessing the impact of nuclear sciences and applications are large, but the results could provide clear justifications to decision makers on economic and social grounds for making the nuclear option the preferred choice.

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