

International Atomic Energy Agency

GENERAL CONFERENCE

GC

GC(46)/INF/5

16 July 2002

GENERAL Distr.

Original: ENGLISH

Forty-sixth regular session

Item 15 of the provisional agenda

(GC(46)/1)

NUCLEAR TECHNOLOGY REVIEW 2002

1. In response to requests by Member States, the Secretariat produces a comprehensive *Nuclear Technology Review* every two years, with a shorter supplement in the intervening years. The present report is the second comprehensive compilation giving a global perspective on nuclear technologies for both power and non-power applications.
2. The NTR-2002 contains an Executive Summary and then reviews the following areas: Fundamentals of Nuclear Development; Nuclear Power, Fuel Cycle and Waste Management; Applications for Food, Water and Health; and Applications for Environment and Sustainable Industrial Processes.
3. The document has been modified to take account, to the extent possible, of specific comments by the Board and other comments received from Member States.

| |
|---|
| <p>For reasons of economy, this document has been printed in a limited number. Delegates are kindly requested to bring their copies of documents to meetings.</p> |
|---|

NUCLEAR TECHNOLOGY REVIEW 2002

Table of Contents

| | |
|--|-----------|
| EXECUTIVE SUMMARY | 4 |
| PART I. FUNDAMENTALS OF NUCLEAR DEVELOPMENT | 7 |
| I-1. NUCLEAR, ATOMIC AND MOLECULAR DATA | 7 |
| I-2. RESEARCH REACTORS, ACCELERATORS AND RADIOISOTOPES | 9 |
| I-2.1. Research Reactors | 9 |
| I-2.2. Accelerators | 11 |
| I-2.3. Radioisotopes | 13 |
| I-3. NUCLEAR INSTRUMENTATION | 14 |
| I-4. NUCLEAR FUSION | 15 |
| PART II. NUCLEAR POWER, FUEL CYCLE AND WASTE MANAGEMENT | 17 |
| II-1. THE GLOBAL NUCLEAR POWER PICTURE | 17 |
| II-1.1. A National and Regional Survey | 17 |
| II-1.2. Public Acceptance | 21 |
| II-2. ADDRESSING THE CENTRAL ISSUES | 24 |
| II-2.1. Rising Energy and Electricity Demand | 24 |
| II-2.2. Sustainable Development and Climate Change | 28 |
| II-2.3. Economic Competitiveness | 29 |
| II-2.4. Advanced Designs | 32 |
| II-2.5. Spent Fuel and Radioactive Waste | 39 |
| PART III. APPLICATIONS FOR FOOD, WATER AND HEALTH | 44 |
| III-1. SUSTAINABLE AGRICULTURE AND FOOD SAFETY | 44 |
| III-1.1. Crop Improvement | 44 |
| III-1.2. Increasing Livestock Productivity | 46 |
| III-1.3. Food Safety | 47 |
| III-2. WATER RESOURCES | 48 |

| | |
|---|-----------|
| III-3. HUMAN HEALTH | 49 |
| III-3.1. Diagnostic Applications | 49 |
| III-3.2. Therapeutic Applications | 51 |
| III-3.3. Nutrition | 54 |
| | |
| PART IV. APPLICATIONS FOR ENVIRONMENT AND SUSTAINABLE INDUSTRIAL PROCESSES | 56 |
| | |
| IV-1. MARINE AND TERRESTRIAL PROTECTION | 56 |
| | |
| IV-1.1. Marine Environment | 56 |
| IV-1.2. Terrestrial Environment | 56 |
| | |
| IV-2. DEMINING | 59 |
| | |
| IV-3. IMPROVING INDUSTRIAL PROCESSES | 59 |
| | |
| REFERENCES | 62 |

EXECUTIVE SUMMARY

1. The unifying theme of the NTR-2002 is the importance of innovation. Innovation makes it possible to step beyond incremental evolutionary improvements constrained by diminishing returns. For crop production and public health, for example, the sterile insect technique created a whole new path for future improvements, distinctly different from applying ever larger amounts of pesticides. Nuclear techniques offer a new and safer approach to removing the world's estimated 60 000 000 abandoned landmines. New precision techniques create the potential for ever less intrusive and more effective radiation treatments for cancer.
2. For nuclear power, continuing innovation will be a key factor in closing the "projection gap" between long-term global energy scenarios in which nuclear power expands substantially and near-term scenarios with only modest expansion or even decline. The former assume that nuclear technologies, like other technologies, are not static. They progress through both evolutionary and innovative improvements. In contrast, technological innovation is of much less importance to the near-term scenarios. While the progress assumed in long-term scenarios is consistent with historical trends, it will not happen by itself. It requires initiative and action to maintain and expand an "innovation culture" throughout the nuclear industry and regulatory community.
3. While the NTR-2002 presents a worldwide review of the state-of-the-art of nuclear science and technology, and not an annual report on IAEA activities, it notes areas where the Agency has a particularly important role to play.
4. Part I of the NTR-2002, "Fundamentals of Nuclear Development", reviews developments in the field of nuclear, atomic and molecular data. New nuclear developments from innovative fuel cycles to landmine detection all need ready access to nuclear data. The Agency's libraries and databases are a central part of providing that access.
5. Research reactors remain essential to progress in nuclear science and technology. Part I reviews advances in radioisotope production, the use of accelerators and neutron activation analysis relevant to applications ranging from medicine – particularly the fight against cancer – to industry. Part I also reviews developments in nuclear instrumentation and nuclear fusion, particularly in connection with the International Thermonuclear Experimental Reactor.
6. Part II begins with a summary of nuclear power production in 2001. At the end of 2001 there were 438 nuclear power plants (NPPs) in operation, corresponding to a total capacity of 353 GW(e), more than 10 000 reactor-years of cumulative operating experience and about 16% of global electricity generation. However, only two new NPPs came online in 2001.
7. Most new NPP construction is in Asia or the economies in transition. The lack of new construction in North America and Western Europe is attributed to economics and to political and public concerns about spent fuel and safety. Part II reviews recent progress and prospects on each count, noting new energy policies in both the United States of America

(USA) and the Russian Federation that are more supportive of nuclear power, and policy reviews are underway in the United Kingdom and European Commission.

8. Part II also reviews innovative reactor and fuel cycle concepts addressing economics, safety, spent fuel and proliferation concerns across different countries. The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the Generation IV International Forum (GIF) initiated by the USA provide largely complementary forums for international cooperation on innovative concepts. Both were launched in 2000. The GIF Charter was formally signed in the summer of 2001. Following an initial meeting of interested parties in November 2000, INPRO's Phase I work plan was approved at the first meeting of its Steering Committee in May 2001. Support for the IAEA initiative was incorporated in a September 2001 General Conference resolution and the December 2001 resolution of the UN General Assembly on the Report of the IAEA. The second and third meetings of the INPRO Steering Committee, in December 2001 and May 2002, have monitored progress and guided preparations for the Phase 1A report.

9. International negotiations on climate change and sustainable development produced mixed outcomes for nuclear power in 2001. At the ninth session of the Commission on Sustainable Development (CSD-9), countries agreed to disagree on the role of nuclear power in sustainable development. There was consensus, however, that "the choice of nuclear energy rests with countries". The seventh session of the Conference of the Parties (COP7) to the United Nations Framework Convention on Climate Change agreed on rules to implement the Kyoto Protocol that were endorsed by a sufficient number of parties to provide entry into force. This is an important step towards attaching a tangible economic value to nuclear power's avoidance of greenhouse gas emissions. However, the COP7 agreement excludes nuclear power projects from two of the Protocol's three flexibility mechanisms, namely joint implementation and the clean development mechanism.

10. Part III reviews the ever-widening global uses of isotopes and radiation, including crop improvements through mutation, evaluation techniques for increasing food production and the expanding use of the sterile insect technique (SIT) to reduce food losses and insecticide use. SIT can also help fight livestock disease by controlling disease-bearing pests. Success in eradicating tsetse fly from Zanzibar has encouraged additional pilot SIT projects in Africa.

11. Food safety through irradiation benefits human health and trade. International efforts and trends are reviewed, with reference to the radioimmunoassay techniques which address the increasing concerns about veterinary drug residues and food contamination.

12. The rapidly expanding use of isotope hydrology and international collaborative efforts are important parts of global efforts to meet growing freshwater needs. In addition, nuclear-powered desalination of seawater is a potentially huge source of fresh water. Current interest is driven by the expanding global demand for fresh water, by concern about greenhouse gas emissions and pollution from fossil fuels and by developments in small and medium-sized reactors that might be more suitable for desalination than large power reactors.

13. The current pace of innovation is particularly rapid in applications of nuclear technologies to human health. Part III covers technological advances in diagnostic radiology, specialist areas of nuclear medicine, and global data and trends for cancer treatment through

radiotherapy and radiopharmaceuticals. Part III also reports recent advances in nuclear and isotopic applications for nutrition monitoring, which are increasingly widely accepted investigative and diagnostic techniques.

14. Part IV reviews the use of nuclear techniques for the safe and healthy use of marine resources. The Agency, in collaboration with other international bodies, improves and applies radiological tracer techniques for research on contaminants in coastal waters, the health of wetlands, marine impacts on freshwater resources and fishing industries. Research indicates that high priority should be given to coastal zone management and submarine groundwater discharges. Global action programmes using radioactive isotopic tracers to monitor oceanographic trends have begun. Similarly, the use of nuclear analytical techniques for the monitoring of pollution in the terrestrial environment is now an accepted practice.

15. For countries plagued by landmines left over from armed conflicts, a promising technique for humanitarian demining using pulsed fast-thermal neutron analysis is under investigation. It will soon be tested in field conditions and will, it is hoped, lead to quicker and safer clearance of minefields.

16. Part IV also reviews applications of radioisotopes and radiation in industry to illustrate their role. Such applications are now indispensable, and are likely to increase across an even wider range of industrial uses.

PART I

FUNDAMENTALS OF NUCLEAR DEVELOPMENT

I-1. NUCLEAR, ATOMIC AND MOLECULAR DATA

Nuclear data describe the properties of atomic nuclei and their interactions with incident particles like neutrons, photons and charged particles. Atomic and molecular data describe interactions of atoms and molecules with free electrons, heavy particles such as protons and alpha particles, and the interaction of the plasma components with wall materials in fusion devices. Major activities on nuclear and atomic data measurements and evaluation are concentrated at the level of national programmes. The nuclear data development work is co-ordinated by the Working Party on International Nuclear Data Evaluation Co-operation (WPEC), which was initiated by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD) and includes the OECD countries as well as Russia and China, which have significant nuclear data programmes. As a WPEC member, the IAEA collectively represents the other countries on this body. The Atomic and Molecular (A+M) Subcommittee of the IAEA's International Fusion Research Council co-ordinates the work on atomic and molecular data. This large body of information constitutes a single pool, which can be accessed through any of the dissemination centres. These centres co-operate through formally established networks that hold regular meetings. The purpose of the networks is to maintain databases, to co-ordinate formats of the databases and retrieval software and to exchange data so that complete information is available to all users regardless of their geographical location. At present, thirteen nuclear reaction data centres and more than twenty nuclear structure and decay data centres form two networks of co-operating centres for nuclear data. The present status of the network databases is shown in Table I-1 [1].

Table I-1. The status of nuclear, atomic and molecular databases at the IAEA

| Database, data library | Present volume |
|--|--|
| Bibliographic information | more than 400 000 entries |
| Experimental nuclear reactions data | 80 344 data sets, 6 162 953 data points |
| Evaluated nuclear reactions libraries | 6 national and international libraries, 516 files in general purpose and more than 15 000 files in specialised libraries |
| Evaluated nuclear structure and decay data | 293 mass chains, each contains from 3 to 37 nuclides |
| Medical isotopes production data | 48 most important reactions |
| A+M Bibliographic | Over 39 000 entries |
| A+M Numerical | Over 4 000 separate reactions represented |

At all centres, CD ROMS or the Internet are replacing magnetic tapes, telnet and hard copies. The total number of serviced requests per year for nuclear data from the IAEA centre is shown in Fig. I-1. The number of requests for atomic and molecular data is comparable.

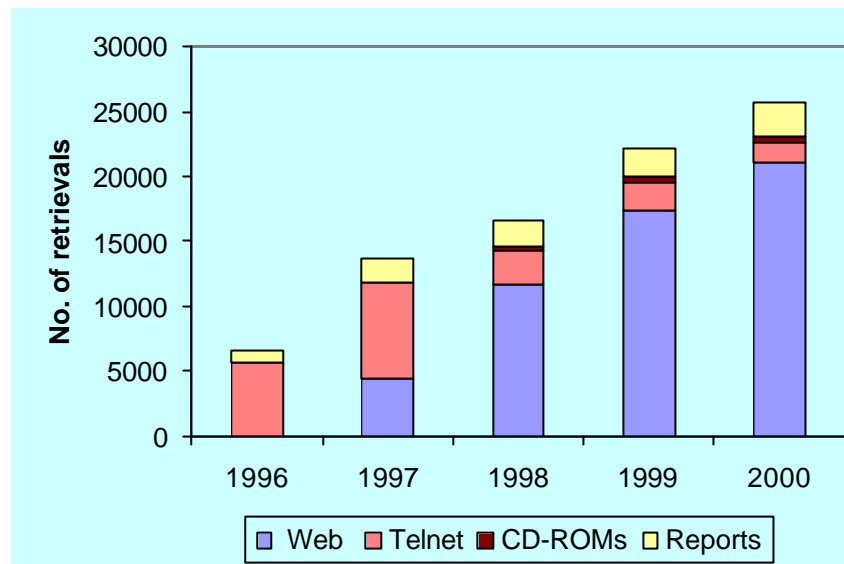


Figure I-1. Retrieval of nuclear data from the IAEA data centre

The IAEA is the main source of information in this area for a large number of Member States, particularly developing countries. In addition to the libraries developed by individual Member States, the IAEA has co-ordinated the development of new libraries through international co-operation. These include:

- The FENDL-2 library of evaluated nuclear data, which has been adopted worldwide for nuclear fusion studies, including those for the International Thermonuclear Experimental Reactor project;
- The IAEA Photonuclear Data Library, which is the first international compilation of data describing complex interactions of photons with nuclei;
- The Reference Input Parameter Library of input data for nuclear model codes, which provides a uniquely identifiable set of input data to evaluators, with integrated links to several frequently used nuclear model codes;
- The AMBDAS searchable database of bibliographic data for atomic and molecular (A+M) processes, which is relevant to nuclear fusion research;
- The ALADDIN numerical database for A+M data, which is also relevant to nuclear fusion research.

The changing requirements of new technologies determine the direction of future database extension and data library development. These new initiatives include data for innovative fuel cycle and reactor concepts, accelerator-driven systems for power generation or radioactive waste incineration, fusion devices, medical treatment, diagnostics with radiation beams, optimization of isotope production, non-destructive materials testing, geology, oil and mineral exploration and landmine detection.

I-2. RESEARCH REACTORS, ACCELERATORS AND RADIOISOTOPES

Radioactive materials, not counting those related to the generation of electricity, were involved in the industrial sector with a sale value of \$330.7 billion in 2001, as per estimates by the Nuclear Energy Institute in the USA [2]. A comparable estimate for Japan was \$69.5 billion [3]. Accelerator-based technologies, namely, ion beam processing and radiation processing for polymerization are key processes in the automobile tyre and semiconductor industries.

I-2.1. Research Reactors

There are currently 277 research reactors in operation plus 17 more planned or under construction [4]. The number of operating research reactors in developed countries peaked in 1975 at 328, and presently stands at 192 (Fig. I-2). The number of operating reactors in developing countries has been increasing, and is 85 at present.

The utilization patterns of research reactors have shifted from providing vital information in nuclear physics during their first three decades and supporting power reactor development towards education, research for materials development and radioisotope production. With the demand for fundamental nuclear research in decline, a significant number of operating research reactors have become service-for-fee facilities performing radioisotope production, radiography, semiconductor doping and neutron activation analysis for a wide range of users. They also continue with their traditional role in education and training.

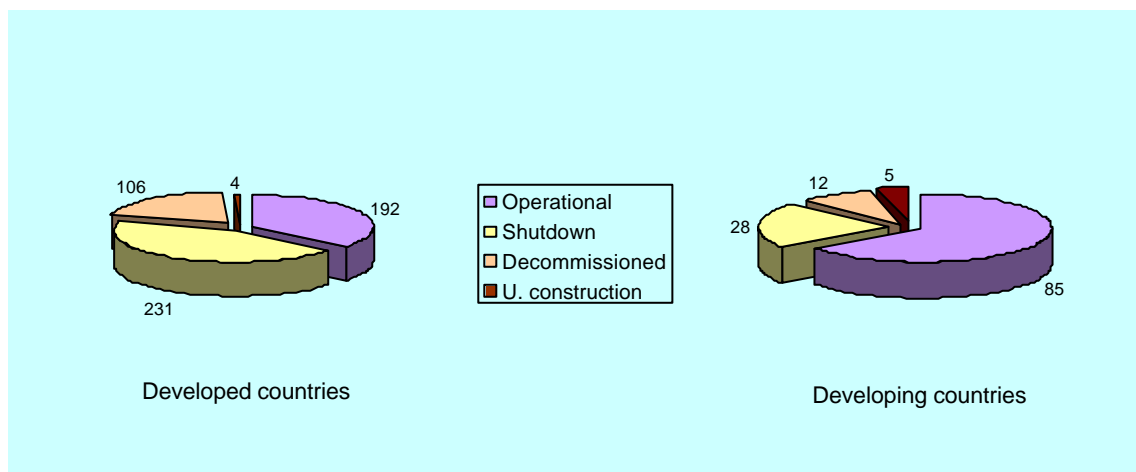


Figure I-2. Operational status of research reactors in the world

Research reactors have been built based on dozens of different designs using a variety of fuel types. A large fraction of today's operational research reactors have a maximum thermal power of 100 kW or less. In the developing countries 33 out of 85 fall in this category as shown in Fig. I-3. Also shown in Fig. I-3 is the age distribution of

research reactors in developing countries. Small reactors have cores that do not require frequent refuelling and the issue of spent fuel disposal is less important. To reduce, and eventually eliminate, commerce in highly enriched uranium for research reactors, the USA established the Reduced Enrichment for Research and Test Reactors Programme, which has been supported since its inception by the Agency and in which the Russian Federation is now a partner.

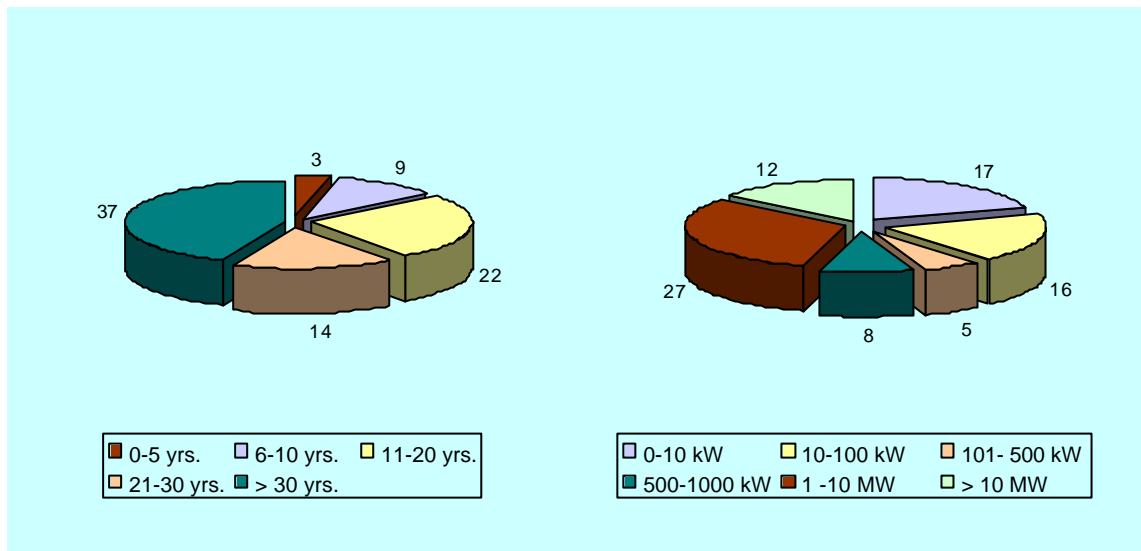


Figure I-3. Age and power distribution of research reactors in the developing countries

Isotopes are produced mainly in reactors having power levels of 1 MW or more. Currently 73 reactors produce radioisotopes, of which six are high flux ($>5 \times 10^{14}$ n/cm²/sec). Some power reactors are also used (mainly for ⁶⁰Co production). The power distribution of isotope-producing reactors in OECD and non-OECD countries is given in Fig. I-4. As can be seen, about half the reactors have power in the range of 5-30 MW. Among the total, about half are more than 35 years old, but 30% of them have been refurbished/upgraded. Two reactors, in Australia and France, will be shut down and replaced with new reactors. In Canada, there is a proposal to build a high flux (3×10^{15} n/cm²/sec) reactor, at an estimated cost of \$466 million, for studying materials.

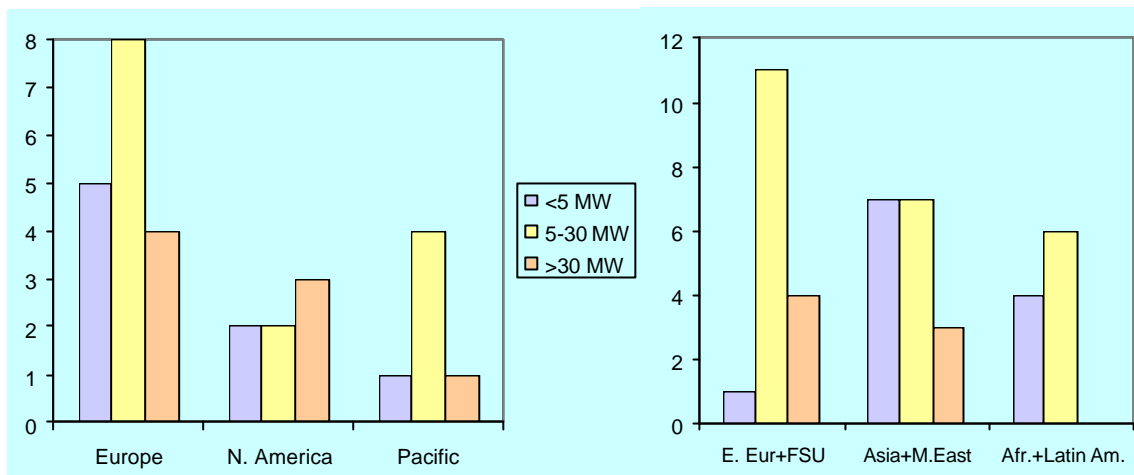


Figure I-4. Number and power distribution of isotope-producing reactors in OECD and non-OECD Countries

Future use of high quality research reactors is expected to be extensive with continuing competition from researchers for access to beam lines with the highest neutron fluxes and cold neutron sources. Many research reactors with moderate performance capabilities will also continue to prosper by exploiting specialized and regional application niches, such as semiconductor doping, test loops for simulating power reactor conditions, radioisotope production and neutron activation analysis. At the same time, many research reactors will continue to fill roles in training the scientists and engineers essential for nuclear power development. The older and under-utilized reactors will probably be shut down and many of the presently shutdown reactors will require funds for decommissioning. (Typically a TRIGA reactor of 1 MW capacity would require ~\$1-2 million for decommissioning.) At present, nine new research reactors are under construction and eight more are planned, including a multipurpose research reactor in Australia and an FRM II in Germany dedicated essentially to neutron beam research. Maple reactors that have recently been built in Canada will be used essentially as commercial isotope factories for producing mainly ^{99}Mo .

I-2.2. Accelerators

Although particle accelerators were originally used for nuclear and particle physics studies, they are now employed in diverse areas of research and technology. Presently, there are about 15 000 accelerators installed worldwide, and the installation rate for new accelerators is approximately 700 per year [5]. A detailed categorization of accelerator usage is given in Fig. I-5.

The major applications of accelerators are ion implantation/surface processing and cancer therapy (Fig. I-5). Linear electron accelerators are extensively used for cancer therapy, and the annual growth in the number of these machines is around 400 to 500 per year. Electron accelerators are also the mainstay for the high-grade polymer industry and are finding increasing applications in the sterilization of medical products and food irradiation (see also Parts III and IV). There are 243 accelerators (mainly cyclotrons) that are used for producing radioisotopes and, of these, 211 are in OECD countries. Among these, 56 are dedicated to general isotope production, 159 to isotope production for positron emission tomography (PET) and 28 cyclotrons are non-dedicated machines.

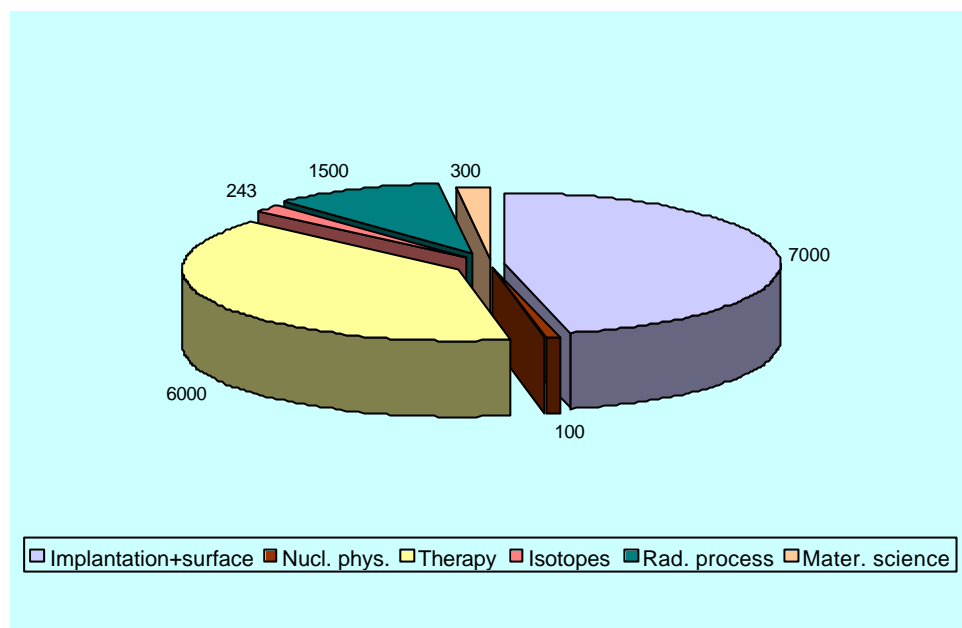


Figure I-5. Usage of particle accelerators

High-energy electron accelerators (energies of several GeV) serve as bright sources of synchrotron light. The use of synchrotron radiation for research in science and technology has grown enormously in the past two decades, and more than 5 000 researchers in Europe alone now make regular use of synchrotron radiation. Worldwide capacity has grown from almost zero in 1970 to 2 million beam line hours per year. In 1999, there were about 45 accelerators in operation as synchrotron light sources. Another 13 are under construction, and about 19 are in the design or proposal stage. In developing countries, at least 7 full-scale accelerators are in operation or expected to be commissioned for synchrotron radiation in the next few years. Prominent applications include research in biosciences, for example in understanding the structure of genes and viruses.

About two hundred accelerators are used worldwide for radioanalytical characterization of materials. In addition, some small accelerator systems are being developed for detecting explosives and drugs.

Looking to the future, the number of operating accelerators is steadily growing, and promising new areas of applications continue to open up. These include the development of new materials, environmental pollution studies, biomedical research, geology, and archaeometry. Accelerator mass spectrometry (AMS) is the most sensitive trace analysis technique currently available, and it is expected that AMS will be used increasingly for trace analysis in oceanography, paleo-climatology and geohydrology.

Spallation neutron sources, based on high-energy proton accelerators, are another area of growth in accelerators. It is expected that the number of spallation neutron sources will increase because of the continuing demand for intense neutron beams. There are five spallation neutron sources currently in operation, with three under construction or planned (USA and Japan).

I-2.3. Radioisotopes

Out of about 800 known radioisotopes, more than 150 are widely used for a variety of applications. These are produced in nearly 73 reactors and 243 accelerators by irradiating suitable targets that are then processed in special radiochemical facilities to make products for different applications. Table I-2 gives a list of prominent applications and the radioisotopes that are used.

As discussed in Section III-3 on human health applications, special radiolabelled compounds (radiopharmaceuticals), which concentrate in selected organs, can help physicians detect malfunctions or metastases in a number of organs and bones. Immunometric methods based on radioisotopes are widely used to determine the concentration of hormones, drugs etc. in blood and other body fluids. Radioisotopes are also essential for medical research. Nearly 30% of all biomedical research involves their use. About 80% of all drugs approved by the US Food and Drug Administration result from research using radioisotopes.

Looking to the future, with many techniques having an important bearing on either industrial activity or health care, the sustainability of radioisotope supplies or “isotope security” has become a major cause of concern in view of the decrease in the number of operating research reactors worldwide. Technetium-99m is expected to retain its dominant role in gamma imaging in the foreseeable future. Advances in molecular biology have led to increased interest in the application of radioisotopes for treatment of diseases. The development of human monoclonal antibodies, peptides and small molecular metabolites, a better understanding of how they interact with cells, and advancement of biological and chemical linking mechanisms have made the concept of a magic bullet a reality. Treatment of an acute form of leukaemia is now possible with radioisotope- (e.g. ^{131}I , ^{213}Bi) labelled monoclonals. Another prominent therapeutic isotope with growing applications is ^{90}Y . The demand for another isotope ^{103}Pd , now used for treating prostate cancer, has also greatly increased. Generator-based ^{188}Re is also emerging as a promising isotope, despite difficulties in its production. Radiopharmaceuticals based on alpha and beta emitters can deliver much higher doses to cancerous tissues than is possible with teletherapy. While conventional external beam therapy is limited to only about 6 000 rad, targeted therapy with radiopharmaceuticals can deliver up to a million rad and is essential for treating cancers like pancreatic cancer. A host of new alpha- and beta-emitting radioisotopes are emerging on the medical scene.

Table I-2. Important radioisotopes, their source of production and different applications

| Application | Source | |
|-------------------------------------|--|--|
| | Reactor | Accelerator |
| Medicine | | |
| 1. Gamma Imaging | $^{99}\text{Tc}^{\text{m}}$, ^{131}I , ^{133}Xe | ^{67}Ga , ^{111}In , $^{81}\text{Kr}^{\text{m}}$, ^{123}I , ^{201}Tl |
| 2. PET Imaging | ^{18}F | ^{18}F , ^{68}Ga , ^{124}I , ^{64}Cu , ^{11}C , ^{13}N , ^{15}O |
| 3. Radioimmunoassay | ^{125}I , ^3H | |
| 4. Radiopharmaceuticals for Therapy | ^{131}I , ^{32}P , ^{90}Y , ^{169}Er , ^{153}Sm , $^{117}\text{Sn}^{\text{m}}$, ^{166}Ho , ^{186}Re , ^{188}Re | ^{211}At |
| 5. Teletherapy | ^{60}Co | |
| 6. Brachytherapy | ^{192}Ir , ^{125}I , ^{137}Cs , ^{198}Au , ^{106}Ru | ^{103}Pd |
| Industry | | |
| 1. Radiation Processing | ^{60}Co | |
| 2. Nucleonic Instrumentation | ^{137}Cs , ^{60}Co , ^{241}Am , ^{85}Kr , ^{147}Pm , ^{90}Sr , ^{204}Tl , ^{14}C , ^{252}Cf , ^{63}Ni , ^{55}Fe , ^{109}Cd , ^{210}Po | ^{57}Co |
| 3. Non-destructive Testing | ^{192}Ir , ^{75}Se , ^{169}Yb | |
| 4. Tracer Studies | ^{47}Sc , $^{113}\text{In}^{\text{m}}$, ^{133}Xe | |

I-3. NUCLEAR INSTRUMENTATION

Nuclear instrumentation is an area with much innovation, resulting in rapid availability of new equipment – but also a high rate of obsolescence. Advances continue to improve energy resolution, detection efficiency, maximum detectable count rate, operating temperature, extended energy range and reduced noise.

The worldwide scene for nuclear instrumentation is currently one of business consolidation of the leading manufacturers, with many companies combining their efforts with other enterprises to provide co-ordinated technical support and services better geared to the needs of their users. For example, one of the world leaders in nuclear fuel cycle technologies has combined with other leading manufacturers of radiation detection and

analysis instrumentation, radiation detection and protection instrumentation and area monitoring systems for nuclear power plants and other facilities.

In general, the new technologies applied in nuclear instrumentation are expected to achieve lower energy consumption, improved reliability, lower cost and better versatility, as well as improved performance. Future instrumentation will be more automated and integrated, and more fully based on digital signal processing technology. As a result of the increased integration of electronic boards, it is expected that significant changes in the training for electronics engineers and technicians will be required. Maintenance of nuclear instruments will be easier and troubleshooting and repair will be increasingly supported by modern communication techniques, such as e-mail and the Internet.

It is expected that the present high levels of innovation and commercial competition in the field will continue for some time, resulting in further specialization, acquisitions and groupings, affecting both existing companies and new enterprises offering nuclear instrumentation. The technological and commercial competition in the field of nuclear instrumentation that has traditionally been dominated mainly by developed countries with extensive industrial infrastructures is expected to open up to developing countries. Currently, in developing countries, expertise in maintaining and servicing nuclear instruments is an important determinant of the rate at which new nuclear techniques in general are assimilated.

I-4. NUCLEAR FUSION

Globally about \$1.5 billion are spent annually on science and technology research related to nuclear fusion. The most probable fuel in a commercial fusion power station would consist of a 50-50 mixture of deuterium and tritium since this mixture fuses at the lowest temperature and its energy yield is the largest compared with other fusion reactions. An additional advantage is the abundance, in particular, of deuterium, which can be extracted from sea water.

Fusion reactants need temperatures of around 100 million degrees Celsius, i.e. temperatures hotter than the interior of the sun, in order to have a self-sustained fusion reaction in which energy output is several times the energy input. At such temperatures, matter is a state called plasma. Special techniques are required for plasma confinement as no construction material can withstand these temperatures. Three methods for plasma confinement exist: (1) gravitational (as occurs in stars), (2) magnetic and (3) inertial. The most successful method for containing plasmas thus far is a magnetic bottle (tokamak) that uses strong externally applied magnetic fields to isolate the hot doughnut-shaped plasma from the reactor structure. About 25 large (up to 10 MW) and medium-sized research tokamaks are in operation in various countries.

Much of current experimental and theoretical research is focused on the International Thermonuclear Experimental Reactor (ITER), an international project based on the tokamak concept. The ITER's purpose is to demonstrate plasma burning and to show that electricity generation by nuclear fusion can be safe and environmentally attractive, although the intensive very high neutron flux levels from fusion might some day also be applied to burn – or transmute – long-lived fission products. Recent ITER results include the completion of

the Engineering and Design Activities (EDA) of a fusion reactor. This work was carried out by the ITER Joint Central Team and the ITER Parties (Europe, Japan, Russia and, until 1999, the USA) under the auspices of the IAEA. The design anticipates the generation of 500 MW of fusion energy per pulse, which is expected to last for several minutes [6]. The output to input energy ratio is expected to be more than ten. Since the start of the EDA in 1992, €330 million has been spent on technology R&D for ITER.

Intergovernmental discussions have begun for the joint implementation of the ITER Project, including decisions on cost sharing and site selection. Canada has offered a site near the Darlington nuclear power station on Lake Ontario, and additional site proposals at Cadarache, France and in Japan are expected. ITER is anticipated to cost about \$3.5 billion and construction may start as early as 2003 [7].

Additional plasma confinement methods are under investigation, including non-tokamak magnetic and inertial confinement devices. An example of the former is a stellarator project, presently under construction in Greifswald, Germany, costing €25 million. Large inertial confinement devices are under construction in France, Japan and the USA. The National Ignition Facility, for example, is a multi-billion dollar, 192-beam, 1.8 MJ laser facility under construction in Livermore, California, USA.

PART II

NUCLEAR POWER, FUEL CYCLE AND WASTE MANAGEMENT

II-1. THE GLOBAL NUCLEAR POWER PICTURE

II-1.1. A National and Regional Survey

II-1.1.1. Worldwide Survey

Worldwide there were 438 nuclear power plants (NPPs) operating at the end of 2001 [8], representing 353 GW(e) of generating capacity.¹ This included six new NPPs first connected to the grid in 2000 – one in Brazil, one in the Czech Republic, three in India and one in Pakistan – plus two new NPPs in 2001, one in Japan and one in the Russian Federation. There were three retirements in 2000 – Chernobyl-3 in Ukraine and two units at Hinkley Point A in the United Kingdom – and no retirements in 2001. Nuclear power's share of global electricity generation in 2000 was 15.9%, down slightly from 16.1% in 1999 [9]. In terms of capacity, NPPs were 10.2% of global electricity generating capacity at the end of 2001, marginally down from 10.4% at the end of 1999. Construction started on five additional NPPs in 2000 – one in China, two in India and two in Japan. In 2001 construction started on one NPP in Japan. Altogether there were 32 NPPs under construction worldwide at the end of 2001. Most current construction is in Asia or the economies in transition.

The most significant trend in recent years has been that of steady increases in NPP availability factors through improvements in operational practices, engineering support, strategic management, fuel supply and spent fuel disposition. These have reduced costs and improved safety. Their cumulative impact has been substantial – since 1990 they have increased availability factors by an amount equivalent to the building of 33 GW(e) of new capacity.

¹ In this report, we use the phrase “nuclear power plant”, or NPP, to refer to a single nuclear reactor unit. Unless otherwise specified, NPP capacity figures refer to *net* electrical generating capacities. Other important definitions used in the IAEA PRIS are the following. **Construction Start:** Date of the first major emplacement of concrete, usually for the base mat of the reactor building. **First Criticality:** Date when the reactor goes critical for the first time. **Grid Connection:** Date when the plant is first connected to the electricity grid to supply power. *After this date, the plant is considered in operation.* **Commercial Operation:** Date when the plant is handed over by the contractors to the owner and declared officially in commercial operation. **Shutdown:** Date when the plant is officially declared to be shut down by the owner and taken out of operation permanently.

Table II-1. Nuclear power reactors in operation and under construction in the world
(as of January 2002)

| COUNTRY | Reactors in Operation (1 Jan. 2002) | | Reactors under Construction (1 Jan. 2002) | | Nuclear Electricity Supplied in 2001 | | Total Operating Experience to 31 Dec. 2001 | |
|-----------------------------|--|----------------|---|-------------|---|---------------|--|--------|
| | No of Units | Total MW(e) | No of Units | Total MW(e) | TW(e)h | % of Total | Years | Months |
| ARGENTINA | 2 | 935 | 1 | 692 | 6.54 | 8.19 | 46 | 7 |
| ARMENIA | 1 | 376 | | | 1.99 | 34.82 | 34 | 3 |
| BELGIUM | 7 | 5 712 | | | 44.1 | 58.03 | 177 | 7 |
| BRAZIL | 2 | 1 901 | | | 14.35 | 4.34 | 21 | 3 |
| BULGARIA | 6 | 3 538 | | | 18.24 | 41.55 | 119 | 2 |
| CANADA | 14 | 10 018 | | | 72.35 | 12.85 | 447 | 2 |
| CHINA | 3 | 2 167 | 8 | 6 426 | 16.68 | 1.14 | 26 | 5 |
| CZECH REPUBLIC | 5 | 2 560 | 1 | 912 | 14.75 | 19.76 | 63 | 9 |
| FINLAND | 4 | 2 656 | | | 21.88 | 30.54 | 91 | 4 |
| FRANCE | 59 | 63 073 | | | 401.30 | 77.07 | 1 228 | 2 |
| GERMANY | 19 | 21 283 | | | 162.30 | 30.52 | 610 | 1 |
| HUNGARY | 4 | 1 755 | | | 14.13 | 39.09 | 66 | 2 |
| INDIA | 14 | 2 503 | 2 | 980 | 17.32 | 3.72 | 195 | 5 |
| IRAN | | | 2 | 2 111 | | | 0 | 0 |
| JAPAN | 54 | 44 289 | 3 | 3 696 | 321.94 | 34.26 | 1 016 | 4 |
| KOREA REPUBLIC OF | 16 | 12 990 | 4 | 3 820 | 112.13 | 39.32 | 185 | 2 |
| LITHUANIA | 2 | 2 370 | | | 11.36 | 77.58 | 32 | 6 |
| MEXICO | 2 | 1 360 | | | 8.11* | 3.66* | 19 | 11 |
| NETHERLANDS | 1 | 450 | | | 3.75 | 4.16 | 57 | 0 |
| PAKISTAN | 2 | 425 | | | 1.98 | 2.86 | 31 | 10 |
| ROMANIA | 1 | 655 | 1 | 650 | 5.05 | 10.46 | 5 | 6 |
| RUSSIAN FEDERATION | 30 | 20 793 | 2 | 1 875 | 125.36 | 15.40 | 701 | 5 |
| SOUTH AFRICA | 2 | 1 800 | | | 13.34* | 6.65* | 34 | 3 |
| SLOVAKIA | 6 | 2 408 | 2 | 776 | 17.10 | 53.44 | 91 | 0 |
| SLOVENIA | 1 | 676 | | | 5.03 | 38.98 | 20 | 3 |
| SPAIN | 9 | 7 524 | | | 61.07 | 26.87 | 201 | 2 |
| SWEDEN | 11 | 9 432 | | | 69.20 | 43.85 | 289 | 1 |
| SWITZERLAND | 5 | 3 200 | | | 25.29 | 35.96 | 133 | 10 |
| UNITED KINGDOM | 33 | 12 498 | | | 82.34 | 22.44 | 1 270 | 2 |
| UKRAINE | 13 | 11 207 | 4 | 3 800 | 71.67 | 46.36 | 253 | 10 |
| UNITED STATES of AMERICA | 104 | 97 860 | | | 768.83 | 20.35 | 2 663 | 8 |
| Total | 438 | 353 298 | 32 | 28 438 | 2 543.68 | | 10 256 | 3 |

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

— 6 units, 4 884 MW(e) in operation; 2 units, 2 700 MW(e) under construction;

— 34.09 TW(e)h of nuclear electricity generation, representing 21.57% of the total electricity generated there;

— 122 years of total operating experience.

Values with an asterisk are IAEA estimates.

† Out of 22 Canadian nuclear units in total, 14 are currently operating and eight are laid up.

Table II-1 summarizes the data as of the beginning of 2002. It shows that nuclear capacity is concentrated in industrialized countries. Nuclear power's share of electricity generation is highest in Lithuania and France at 78% and 77% respectively. Cumulative operating experience by the end of 2001 was over 10 000 reactor-years.

II-1.1.2. Regional and National Survey of the Status and Trends of Nuclear Power

In North America, the near-term future for nuclear power is driven primarily by economics. The most important trends are liberalized electricity markets and, consequently, improved NPP performance. Liberalization has largely prompted lower generating costs, higher capacity factors, consolidation, acquisitions, upratings and licence extension applications rather than new construction as selected companies move to define themselves largely by the size and expertise of their nuclear operations. For the moment, continuous management improvements to increase the profitability of existing NPPs is viewed as a more promising and less risky strategy than embarking on new construction.

No new NPP has been ordered in the USA since 1978, although seven units that were out of service for extended periods have been restarted since 1998. No new nuclear capacity is under construction. However, the Nuclear Energy Institute (the US nuclear industry's lobbying group) is advocating as much as 50 GW(e) of new nuclear capacity by 2020, and the new US energy policy released by the White House in May 2001 recommends government support for "the expansion of nuclear energy in the United States as a major component of our national energy policy." In February 2002 US Secretary of Energy Spencer Abraham announced "Nuclear Power 2010", a government commitment to work with industry to explore sites and "support the process to receive US Nuclear Regulatory Commission Early Site Permit approval", with the goal of a new NPP operating in the USA before the end of 2010.

In Canada, near-term expansion of nuclear generation will probably be in the form of restarting some or all of the eight nuclear units (out of a Canadian total of 22) that are currently laid up. In February 2001, the Canadian Nuclear Safety Commission completed a favourable environmental assessment of restarting four units now laid up at Pickering A. In May 2001, Ontario Power Generation Inc. leased the eight-unit Bruce nuclear station to Bruce Power, a joint venture of British Energy and Cameco. Four of the Bruce units are currently operating, and four are laid up. Bruce Power is evaluating the possible restart of two of the laid-up units. With their restart, six new NPPs would come online, representing an additional nuclear net capacity of 3 598 MW(e) worldwide.

Western Europe currently has 150 reactors. Overall capacity is likely to remain at or near existing levels in the coming years, even with policy-directed nuclear phase-outs in, particularly, Belgium, Germany and Sweden. In Germany, the effect of the phase-out agreement will be to reduce the number of reactors in operation to 13 by the end of 2010, with nuclear generating capacity down to 17.4 GW(e). In Sweden, one unit has been taken out of service permanently. Barsebäck-2 is the second unit scheduled for premature retirement. It was to have been shut down by the end of 2001, but that has been postponed and no new definite shutdown date has been set.

The last new NPP to be connected to the grid in Western Europe was Civaux-2 in France in 1999, and none is under construction. The most significant possibility for new nuclear capacity is in Finland. In November 2000, the utility Teollisuuden Voima Oy (TVO) applied for a Government decision "in principle" to build a fifth Finnish NPP. In January 2002 the Government made a favourable decision, which was ratified by the Parliament in May. TVO now has a five-year window in which to apply for a construction permit.

In Western Europe also liberalization has led to cost reductions and productivity improvements. Many countries have already gone beyond the requirements in *Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity*, with the result that two-thirds of the electricity market has been opened up (although intra-Community trade still accounts for only 8% of total electricity production) and prices to industrial consumers have fallen significantly. One impact of price decreases driven by liberalization has been the closure, or proposed closure, of excess capacity.

In Eastern Europe there are 69 reactors totalling 46 GW(e) of installed capacity. Ten NPPs are under construction. The Russian Federation was the only country in the region to connect a new NPP to the grid in 2001 – Rostov-1. This brought the total number of NPPs in the Russian Federation to 30 at ten sites, with a total capacity of 20.8 GW(e). Two reactors, representing an additional 1.9 GW(e) of capacity, are under construction at Kalinin and Kursk.

The European Union continues to seek the closure of first-generation water-cooled WWER and graphite-moderated RBMK reactors in Eastern Europe. The EU is pressing Bulgaria, which has agreed to shut Kozloduy-1 and -2 by 2003 to also shut Kozloduy-3 and -4 by 2006, rather than continue with modernization plans. Bulgaria has emphasized that decisions on Kozloduy-3 and -4 will only be taken after the update of Bulgaria's National Energy Strategy later this year. Slovakia has announced the closure of Bohunice-1 and -2 in 2006 and 2008, respectively. Lithuania has agreed to early closure of Ignalina-1 in 2005 and, in June 2002, reached an agreement in principle with the EU, according to which Lithuania will receive "adequate and additional financing" from the EU to shut down Ignalina-2 in 2009. Negotiations on details, including how much money the EU will provide, were scheduled to begin in July 2002. At the same time, several countries have helped to finance safety upgrades at other Eastern European NPPs through the Nuclear Safety Account, which is administered by the European Bank for Reconstruction and Development.

In the Far East there are 79 operating NPPs. Seventeen are under construction, and at least 19 more are planned. Capacity and production are greatest in Japan, with 54 NPPs totalling 44.3 GW(e). Three new plants are currently under construction, with plans to start construction on another six NPPs between 2002 and 2011. Like the Republic of Korea (with 16 NPPs in operation and four under construction), Japan's interests in nuclear power, and the more competitive economics of new NPPs in Japan, are partly due to a relative lack of indigenous energy resources and consequent concerns about supply diversity and security. Nuclear power also plays an important role in Japan's plans for meeting its Kyoto Protocol commitment to reduce greenhouse gas emissions in 2008-2012 by 6% relative to 1990. Three NPPs are in operation in China, all of which came online in the 1990s. Eight more are under construction. Taiwan, China has six NPPs with two more under construction.

India has 14 NPPs. All are relatively small, with individual capacities up to 202 MW(e). The country's longer-term objective is to have 20 GW(e) of (gross) capacity by 2020. To this end, India is developing fast breeder reactors to make use of its extensive indigenous thorium reserves. In addition to the two units of 490 MW(e) under construction in Tarapur, there are firm plans to build four more 202 MW(e) PHWRs at Kaiga, four 490 MW(e) PHWRs at Rajasthan and two Russian-designed 950 MW(e) WWERs at Kudankulam. For the Kudankulam plants clearance for excavation work was given in November 2001.

In Latin America there are six operating NPPs, two each in Argentina, Brazil and Mexico. In national submissions to the IAEA, only Atucha-2 in Argentina is currently reported as "under construction", although Angra-3 in Brazil is 59% complete. In December 2001 the Brazilian National Energy Council authorized new studies, to be completed in 2002, on finishing Angra-3.

The only African country with operating NPPs is South Africa. Eskom, which operates the two 900 MW(e) PWRs at Koeberg, also leads an international consortium developing the PBMR. Assuming the necessary regulatory and legislative approvals are forthcoming on schedule, initial landscaping of a PBMR site could start in 2003 and actual construction in 2004. The PBMR concept envisages a number of small (~100 MW(e)) modularly designed reactors that can be built relatively quickly and expanded to provide power stations at different scales as needed. Section II-2.4, on advanced and innovative reactor designs, discusses the PBMR further.

II-1.2. Public Acceptance

Belgium, Germany and Sweden have policies to phase out nuclear power. In Austria, Denmark, Greece, Ireland, Italy and Norway it is banned. These policies reflect issues of political and public acceptance for nuclear power that do not apply to other energy sources, none of which faces categorical restrictions comparable to those that these countries apply to nuclear power. This section summarizes nuclear power's special political and public acceptance issues.

The issues on which debate is most often focused are four: economics, safety, waste and proliferation. Sections II-2.3 and II-2.5 address the issues of economics and waste respectively. This section summarizes safety and proliferation considerations, as well as how all four issues are considered together in choosing the right balance of different energy sources. It also includes a short section on nuclear security in the context of terrorism.

II-1.2.1. Safety Concerns

Safety information and recent developments related to all nuclear applications are covered in detail in the IAEA's annual *Nuclear Safety Review* and are not repeated here. This section provides a brief summary of key features related to the public and political acceptability of nuclear power.

Comparative assessments of the health and environmental risks of different electricity generation systems show that nuclear power and renewable energy systems are at the lower end of the risk spectrum. Significant health impacts from nuclear power arise only from major accidents, of which there has been one – the 1986 Chernobyl accident. Its causes were serious design flaws coupled with serious operator mistakes. Since the accident, there have been major improvements in nuclear plant safety through the enhancement of the nuclear safety culture and the application of advanced technology to improve engineering and design safety features. The global safety record for nuclear power plants has shown continued improvement, with marked progress in safety modernization of reactors in Central and Eastern Europe. Also since the Chernobyl accident, the comprehensive exchange of information on operational safety experience has become a major factor in nuclear safety improvements worldwide. International mechanisms to facilitate exchange include the World Association of Nuclear Operators (WANO) and the IAEA. WANO was created in the aftermath of the Chernobyl accident to foster information exchange, comparison, emulation of best practice and communication among members. The IAEA's activities include safety review and assessment missions, the establishment of internationally recognized safety standards and activities in support of the Convention on Nuclear Safety.

WANO monitors safety system performance at NPPs and provides detailed reports directly to its members. Because its safety system performance indicators are defined to reflect differences among NPP designs, they cannot be summarized across reactor types and are not included in WANO's publications. Figures II-1 and II-2, however, show improvements in two publicly available WANO indicators related to safety improvements, the number of unplanned automatic scrams per 7 000 hours critical and the industrial accident rates at NPPs.

The broad acceptability of current reactor safety levels is demonstrated by the continued successful operation of reactors all over the world. The safety debate today is largely in the context of the European Union's efforts to accelerate closure of first-generation water-cooled WWER and graphite-moderated RBMK reactors in Eastern Europe. As with other technologies (e.g. aeroplanes, automobiles and buildings in earthquake zones), new ideas and engineering advances mean that there will always be room for safety improvements. Thus, even with the broad acceptability of today's NPP safety levels, continuing innovation and safety advances will remain an essential objective of all new reactor and fuel cycle designs as discussed in Section II-2.4.

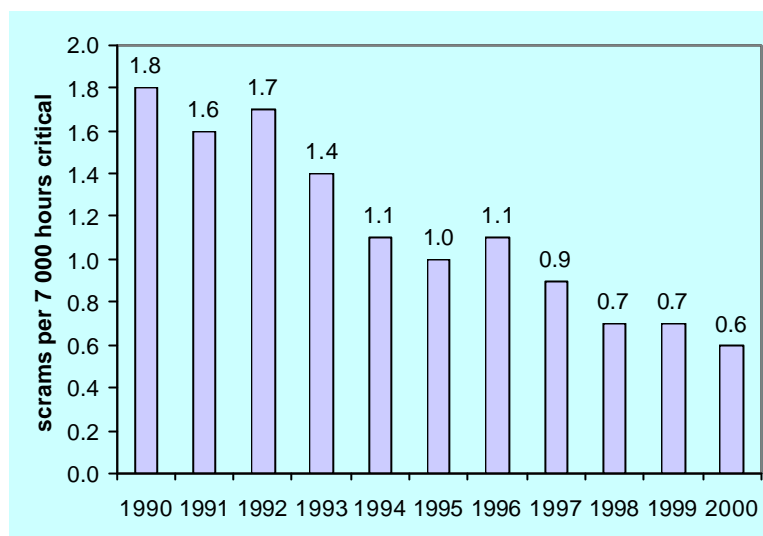


Figure II-1. Unplanned automatic scrams per 7 000 hours critical

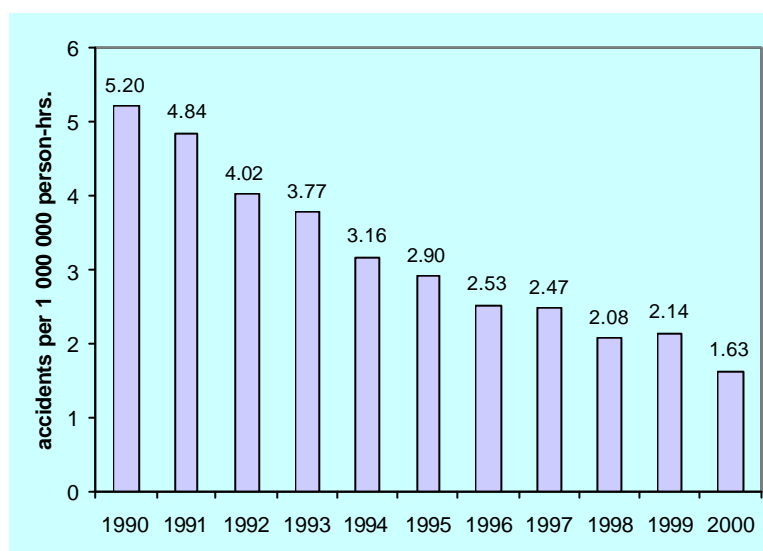


Figure II-2. Industrial safety accident rate, number per 1 000 000 man-hours worked

II-1.2.2. Proliferation Resistance

The international non-proliferation regime consists of the Treaty on the Non-Proliferation of Nuclear Weapons and comprehensive IAEA safeguards agreements, including additional protocols now in force in 24 countries², international verification measures (the IAEA safeguards system plus regional agreements and bilateral agreements) and export controls.

A full account of IAEA safeguards activities has been provided in the Agency's *Safeguards Implementation Report* for the year 2001. In addition to the important challenges

² As of 31 December 2001.

of strengthening the safeguards system, the technical challenge is to design new nuclear facilities with more proliferation resistant features.

II-1.2.3. Security

In response to a request from the General Conference at its meeting in September 2001 (GC(45)/RES/14), the Director General submitted a report entitled Protection Against Nuclear Terrorism to the Board of Governors in November 2001, and a revised report to the Board in March 2002. The Board approved in principle the proposed activities and funding arrangements and stressed the urgency of adequate financing.

II-1.2.4. Comparative Assessment

In idealized markets, all costs associated with a technology would be internalized as part of its economic cost, and decisions based solely on economic costs would automatically properly reflect all social considerations. Nuclear energy is largely ahead of other energy technologies in internalizing its external costs. The costs of waste disposal, decommissioning and meeting safety requirements are in most countries already included in the price of nuclear electricity. Progress towards a more level playing field where external costs of other energy technologies are more consistently internalized as part of their economic costs would facilitate comparative assessment. As indicated by the results of the ExternE studies in Europe [10], external costs for fossil-fired plants operated to current standards are well above external costs of NPPs, also operated to current standards.

In 2001, significant, although still incomplete, progress was made concerning greenhouse gas emissions as summarized in Section II-2.2. This and energy supply security³ both received increased attention in, among other policy deliberations, the new US energy policy published in May 2001, the European Union's November 2000 Green paper *Towards a European strategy for the security of energy supply* and the European Parliament resolution in November 2001.

II-2. ADDRESSING THE CENTRAL ISSUES

II-2.1. Rising Energy and Electricity Demand

Worldwide, energy use is projected to increase substantially throughout the 21st century. The driving forces are population growth and economic development, particularly in developing countries. The most recent comprehensive projections are those published in the Intergovernmental Panel on Climate Change's *Special Report on Emissions Scenarios* (SRES) in 2000. In the 40 reference scenarios in the SRES, global primary energy use grows by a factor of 1.7 - 3.7 by 2050, with a median increase by a factor of 2.5. Electricity demand grows even faster because economic growth consistently prompts a shift towards electricity. People prefer its cleanliness at the point of end-use, its convenience and its flexibility.

³ Nuclear energy contributes to supply security because (1) uranium is available from diverse stable producer countries and (2) small volumes are required, making it easier to establish strategic inventories.

By 2050, the IPCC's projected electricity growth is by a factor of between two and eight. The median increase is by a factor of 4.7.

By design none of the 40 SRES scenarios includes policies to mitigate climate change. The IPCC's subsequent *Third Assessment Report* (TAR), however, reports results for 76 post-SRES stabilization scenarios that do incorporate such policies [11]. Because of limits on carbon emissions in the TAR scenarios, energy use does not grow as quickly as in the SRES scenarios, but it still grows substantially. Although results for all 76 scenarios are not generally available, a subset of 19 TAR scenarios has been analysed by Riahi and Roehrl [12] and is included in the discussion here.

It should be noted that all the SRES and TAR scenarios include substantial improvements in final energy intensities⁴ of between 1% and 2.5% per year. Improvements during the 20th century averaged about 1% per year, and the scenarios thus assume that the potential for further efficiency improvements continues to be exploited at a generally accelerating pace. Going one step further, the SRES scenarios include a set of very Green scenarios with extensive conservation and efficiency improvements and lifestyle changes. Although both population and energy use in these grow more slowly than the median – even to the extent that absolute energy use in OECD countries *decreases* – global energy use still rises in all cases until at least late in the 21st century. Even in Green scenarios in which the global population peaks as early as 2050 at only 8.6 billion, economic growth in developing countries still translates into overall global energy growth.

Nuclear capacity projections in the SRES scenarios cited above are shown as the vertical bars in Fig. II-3. Projections for the 19 TAR scenarios analyzed by Riahi and Roehrl (which are not shown in the figure) would be slightly higher. For the SRES scenarios in 2050 the projected nuclear capacities range between the current value of 350 GW(e) up to more than 5 000 GW(e) (with a median of more than 1 500 GW(e)). This would require adding 50-150 GW(e) per year from 2020-2050. For the 19 TAR scenarios, projections for 2050 range from 2 300 GW(e) of nuclear capacity up to more than 7 000 GW(e) (with a median of more than 4 400 GW(e)). This would require additions of 50-205 GW(e) per year from 2020-2050, besides new NPPs required to replace old NPPs retired during that period.

Figure II-3 also shows two distinctly lower intermediate-term projections (up to 2020) for nuclear power. First are the projections of the IAEA shown by the yellow triangle. The bottom side of the yellow triangle is the IAEA low projection; the upper side is the IAEA high projection. These are based on annual IAEA reviews of specific projects, national plans and national projections. The IAEA low projection (see also Table II-2) essentially assumes no new nuclear plants beyond what is already being built or seriously planned today, plus the retirement of old nuclear plants, and results in a 9% drop in nuclear electricity generation by 2020. The IAEA high projection estimates a 53% increase with capacity increases only slightly below the SRES median. The last projection in Fig. II-3 is the International Energy Agency's (IEA's) reference case. In the figure it is indistinguishable from the IAEA low

⁴ Final energy intensity is defined as the ratio of the sum of energy delivered to the end-user over gross domestic product and serves as a proxy for energy efficiency improvements at the level of end-use, for structural economic change and for behavioural change.

projection (the bottom side of the yellow triangle), although it projects only a 3% decrease in global nuclear electricity generation from 2000 to 2020 – rather than the IAEA’s 9%.

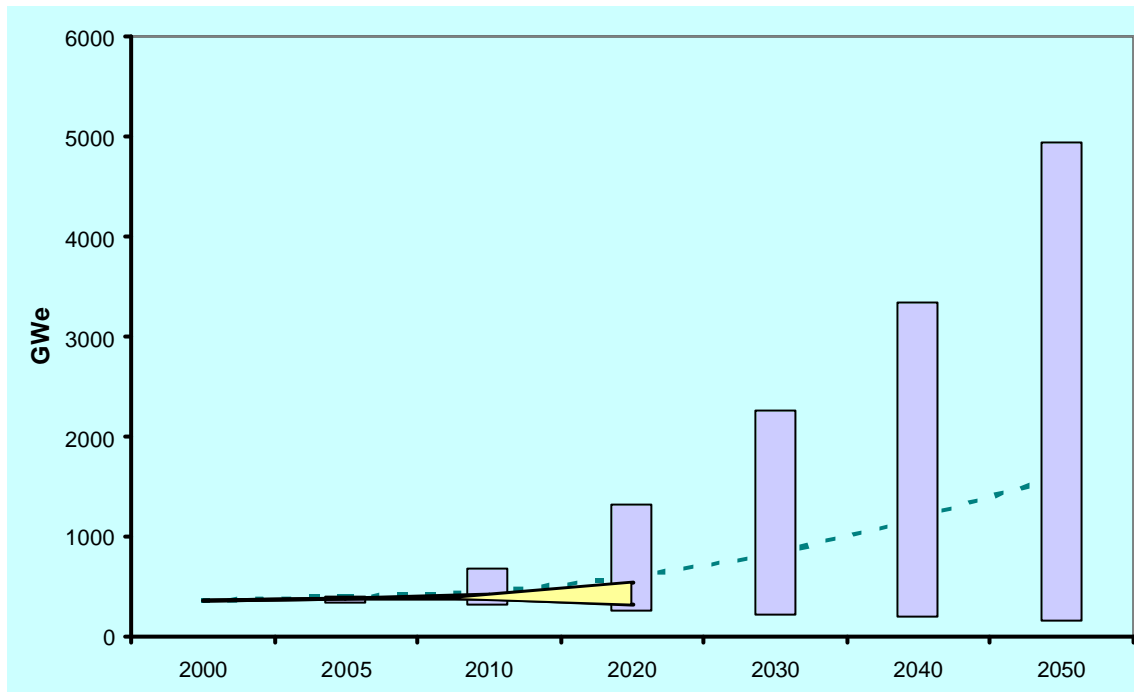


Figure II-3: Nuclear capacity projections from three sets of scenarios. The vertical bars show the range projected in SRES, with the dotted line indicating the SRES medians. The yellow triangle shows the range between the IAEA high and low projections through 2020.

The “projection gap” between the intermediate-term scenarios of the IAEA and IEA and the long-term scenarios in SRES and TAR is largely due to differing assumptions about political constraints, cost improvements and innovation. The absence of new Western European or North American NPPs in the IEA and low IAEA projections assumes hostile or indifferent political environments, no innovation and little or no progress on new NPP costs. The long-term SRES and TAR scenarios, in contrast, assume, first, that nuclear technologies, like other technologies, are not static and, second, that in the long term investments are made ultimately on the basis of economics. In these scenarios, the nuclear industry makes continuing cost reductions, introduces innovations and is able to sell NPPs based exclusively on their cost and performance in a politically neutral market. A number of the SRES and TAR scenarios also assume that an increasing share of nuclear energy is used for innovative non-electric applications, including hydrogen production for both the transport sector and stationary uses.

Table II-2. Estimates of total electricity generation and contribution by nuclear power

| Country Group | 2000 | | | 2005 | | | 2010 | | | 2020 | | | |
|---------------------------------|-------------------|---------|--------|-------------------|------------|------------|-------------------|------------|------------|-------------------|-------------|------------|----|
| | 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 | 4586 | 822.6 | 17.9 | 4951 5097 | 832 838 | 17 16 | 5349 5660 | 809 842 | 15 15 | 6004 6690 | 659 978 | 11 15 | |
| Latin America | 1029 | 19.7 | 1.9 | 1138 1245 | 25 25 | 2.2 2.0 | 1273 1556 | 27 43 | 2.1 2.7 | 1623 2434 | 28 79 | 1.8 3.3 | |
| Western Europe | 2937 | 842.7 | 28.7 | 3147 3249 | 820 838 | 26 26 | 3377 3594 | 796 844 | 24 23 | 3901 4377 | 596 991 | 15 23 | |
| Eastern Europe | 1716 | 274.3 | 16.0 | 1803 1900 | 295 308 | 16 16 | 1897 2115 | 311 342 | 16 16 | 2231 2868 | 210 417 | 9.4 15 | |
| Africa | 441 | 13.0 | 2.9 | 482 512 | 13 14 | 2.7 2.7 | 538 620 | 13 14 | 2.5 2.3 | 703 921 | 14 30 | 1.9 3.2 | |
| Middle East and South Asia | 1112 | 15.3 | 1.4 | 1264 1365 | 19 22 | 1.5 1.6 | 1494 1714 | 35 40 | 2.3 2.4 | 2011 2610 | 41 91 | 2.0 3.5 | |
| South East Asia and the Pacific | 581 | | | 669 719 | | | 776 902 | | | 1009 1331 | | | |
| Far East | 3006 | 461.4 | 15.3 | 3205 3590 | 566 586 | 18 16 | 3453 4359 | 670 767 | 19 18 | 4317 6306 | 692 1160 | 16 18 | |
| World Total | Low Estimate | 15407 | 2448.9 | 15.9 | 16659 | 2571 | 15 | 18157 | 2660 | 15 | 21798 | 2240 | 10 |
| | High Estimate | | | | 17677 | 2632 | 15 | 20520 | 2893 | 14 | 27539 | 3758 | 14 |

Closing the projection gap in Fig. II-3 thus requires success on two fronts. First, through evolutionary and innovative improvements, the nuclear industry must continually reduce costs. Section II-2.4 discusses innovation and progress on new designs in more detail. Second, progress must also be made on political and public acceptance issues as discussed in Section II-1.2. Neither will happen by itself. The first will require continuing innovative R&D on the part of industry and governments. The second will require continuing public and political discussion of the pros and cons of all energy options.

Resources

None of the three projections discussed above, including the 100-year SRES and TAR projections, suggests that nuclear power's future will be constrained by a shortage of economically available nuclear resources, although substantial exploration and development will be required to assure that these resources are really usable. The long-term SRES and TAR scenarios also assume continuing innovation in nuclear reactor designs and fuel cycles to steadily improve the efficiency with which nuclear resources are used. Overall they see nuclear energy's future as neither immediately limited by resource constraints, nor guaranteed by a shortage of affordable fossil fuels or by strict limits on greenhouse gas emissions. More generally, SRES and TAR conclude that the world's energy future will most likely not be determined by one or more sources of energy running out.

Looking at nuclear resources in the near term, uranium prices dropped steadily from mid-1996 up to the end of 2000, with the spot market reaching \$18.64/kgU (\$7.10/lb U₃O₈)

by 31 December 2000. Market prices have since begun to rise, driven by industry consolidation and reduced production capacity, standing at \$24.90/kgU (\$9.50/lb U₃O₈) on 5 December 2001. For a number of years, uranium production has been about half the rate of uranium consumption, the difference being made up from secondary supply sources, including uranium inventories, conversion of nuclear weapons material to commercial reactor fuel, reprocessing of spent nuclear fuel, and, to a very limited degree, re-enrichment of depleted uranium (tails). Substantial contributions from secondary supply are likely to limit demand for newly produced uranium in the near-term, led by the increasing availability of material from dismantling nuclear weapons. Therefore, the general expectation continues to be that any upward pressure on uranium prices is likely to be modest for the immediate future.

II-2.2. Sustainable Development and Climate Change

In April 2001 at the ninth session of the Commission on Sustainable Development (CSD-9), parties agreed to disagree on nuclear energy's role in sustainable development. The final text notes that some countries see nuclear energy as a substantial contributor to sustainable development while others consider the two to be fundamentally inconsistent. However, the parties did reach unanimous agreement that, "the choice of nuclear energy rests with countries".

The Conference of the Parties to the United Nations Framework Convention on Climate Change reached agreement in November 2001 on implementation rules (referred to as the Marrakesh Accords) for the Kyoto Protocol. For nuclear energy this is an important step towards attaching a tangible economic value to nuclear power's avoidance of greenhouse gas (GHG) emissions. Currently the fact that nuclear power produces virtually no greenhouse gases is an advantage that is invisible to investors. Except for a very few instances, there have been no restrictions or taxes on greenhouse gas emissions and thus no economic value to their avoidance. Particularly in liberalized energy markets, binding restrictions on GHG emissions are needed if nuclear power's advantage of very low emissions is ever to matter to investors. And at the moment, the Kyoto Protocol is the world's only operative route toward widespread, coordinated restrictions on GHG emissions. The Marrakesh Accords, however, exclude nuclear projects from two of the three flexible mechanisms in the Kyoto Protocol, the clean development mechanism (CDM) and joint implementation (JI). The IAEA Secretariat has consistently taken the position that in climate change negotiations nuclear power should be judged on its climate change attributes, and the exclusion of any technology with clear climate benefits from any of the flexible mechanisms can only limit options, flexibility and cost-effectiveness. However, the Marrakesh Accords, even with the nuclear exclusion from the CDM and JI, constitute important progress toward restrictions on GHG emissions and thus are better for nuclear energy than no agreement.

Two major events in 2002 are the projected entry into force of the Kyoto Protocol and the August-September 2002 World Summit on Sustainable Development (WSSD). Although the USA remains outside the Kyoto process, enough of the parties to the Marrakesh Accords said they would now ratify the Kyoto Protocol to reach the threshold for entry into force. Entry into force requires ratification by at least 55 parties accounting for 55% of 1990 Annex I carbon emissions. As of 17 June 2002 there were 74 ratifications accounting for 35.8% of 1990 Annex I carbon emissions. The Russian Federation's ratification is necessary

(17.4% of 1990 Annex I carbon emissions), after which either Australia (2.1%), Canada (3.3%) or Poland (3.0%) could push the total over 55%. This is now the critical milestone on which all attention is focused. However, nearly everyone left Marrakesh with improvements that they would like to see made in the agreement, and subsequent negotiations may create opportunities to revisit the nuclear exclusions from the CDM and JI.

The WSSD will review progress since 1992 on implementing Agenda 21. Nuclear science and technologies have had much to contribute to progress on Agenda 21 in nearly all the areas covered in this *Nuclear Technology Review 2002*. As the nuclear expert within the UN family, the IAEA is currently contributing to several UN preparatory processes co-ordinating input to the WSSD on UN contributions to progress over the last decade. For the IAEA, these include the use of nuclear techniques in medical procedures, agriculture, food safety, public health, industrial techniques, water resources and electricity generation, as well as new innovative applications such as landmine detection. They include both the dissemination and technology transfer of existing established applications, and support for nuclear science and basic research in pursuit of new innovative applications. The Agency intends to be well represented in Johannesburg throughout the WSSD to serve as the principal UN information resource on the role of all nuclear technologies in sustainable development.

II-2.3. Economic Competitiveness

Most of the world's electricity markets are now moving towards greater competition, driven in part by technology, and in part by the experience that competitive markets are more self-sustaining. Electricity companies are now in the business of selling a commodity (kWh) and commercial services instead of a strategic good. Increased competition has generally led to lower generation costs compared to more protected and monopolistic market structures. Liberalization has also prompted consolidation, acquisitions, upratings and licence extension applications as selected companies move to define themselves largely by the size and expertise of their nuclear operations.

II-2.3.1. Existing Plants

Well managed existing nuclear power plants have generally fared well in restructured markets. Operating costs of NPPs, including fuel costs, are usually lower than the costs of alternatives, with the exception of hydroelectricity. Capital is largely depreciated, and a plant with operating and maintenance costs below market prices turns a profit. Nuclear production costs in the USA have dropped to an average of 1.83 cents/kWh in 1999 and 1.74 cents/kWh in 2000, with the most efficient plants operating at costs around 1.2 cents/kWh. Nuclear generation costs have also dropped in the United Kingdom from 1.99 pence/kWh to 1.87 pence/kWh in 2000. For Electricité de France they dropped 7% between 1998 and 2000 to 15-18 centimes/kWh, depending upon the site. The cost trend is still downward.

Not all NPPs fall into this category. Although two-thirds of US NPPs produce power for under 2 cents/kWh, others have costs of 6-13 cents/kWh. In the United Kingdom, each of British Energy's eight privatized nuclear stations sells power profitably at competitive market prices (an average of around 3 cents/kWh), while the Magnox plants assigned to BNFL are

still producing at around 5cents/kWh, or are being closed as uneconomic before the end of their design lifetime.

Almost all nuclear plants that are now competitive have made significant if not dramatic improvements over the last decade in their availability and operating costs. Figure II-4 presents the worldwide increase in energy availability factor in the last decade. Individual plant availability increased in many cases by some 30 percentage points. Global energy availability increased from 73% to over 83% in 2001 – the equivalent of adding 33 GW(e) of new generating capacity. In the USA the energy availability factor rose steadily from 80% in 1998 to 89.8% in 2001. The average energy availability factors in Germany, Spain, Finland, Brazil, the Republic of Korea and the Netherlands all exceeded 90% in 2001.

For all these reasons (and because of the high cost of new NPPs discussed immediately below), there is growing interest in lifetime extensions. Ten US NPPs, for example, have been granted lifetime extensions that increase the licensed lifetime of each to 60 years. An additional 40% of operating US plants have indicated an intention to seek licence extensions, and the NRC expects the figure to eventually reach 85% or higher. In 2001, the Ministry of the Russian Federation for Atomic Energy also decided to extend the lifetimes of Novovoronezh-3 and -4 by 15 years.

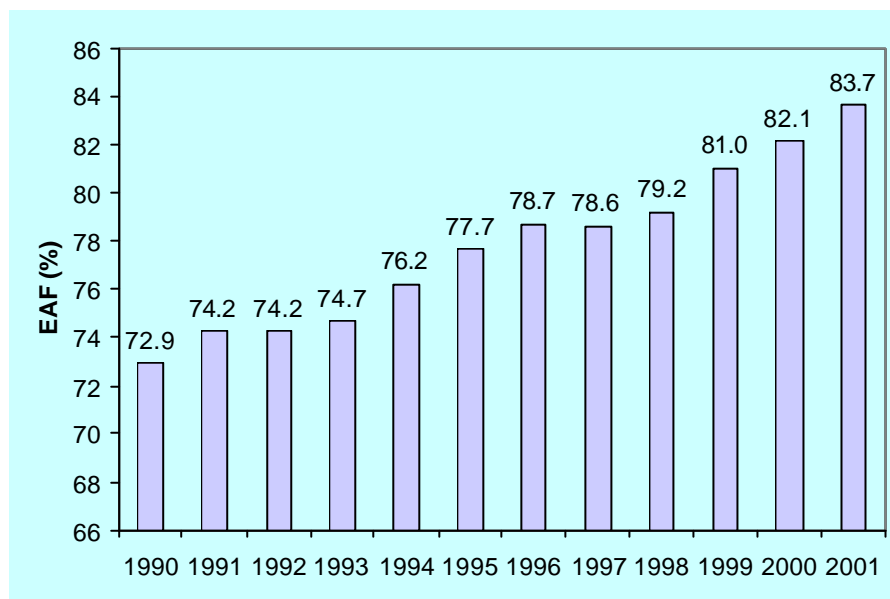


Figure II-4. Global average energy availability factor (EAF)

Applications for power upratings are motivated by many of the same factors. In 2001 upratings calculated from IAEA PRIS data totaled approximately 740 MW(e), with the bulk occurring in North America (about 510 MW(e)) and Western Europe (about 180 MW(e)). The US NRC expects applications for 1 600 MW(e) worth of upratings over the next five years.

II-2.3.2. New NPPs

Managing the financial risks associated with high capital costs, which account for some 70% of total nuclear generating costs, is a major challenge in the financing and building of new nuclear plants. Table II-3 compares capital costs for different alternatives based on OECD and IPCC reports. Although this table shows that new NPPs usually cost two to four times more to build than fossil-fuelled plants, two qualifiers should be kept in mind. First, although Table II-3's ranges for capital costs and generating costs are generally higher for nuclear than other sources, there is enough overlap to make nuclear sometimes the preferred option, particularly in terms of generating costs. Second, the situation is different in different parts of the world. Thus, nuclear power is more competitive in Japan and the Republic of Korea, where fossil fuel prices are high, and high priority is given to energy supply security. This is an important factor in most recent decisions to build new nuclear power plants (e.g. in China, India, Japan and the Republic of Korea), just as it was earlier in countries like France, Germany and Sweden. Nuclear power also plays an important role in Japan's plans for meeting its Kyoto Protocol commitment to reduce greenhouse gas emissions.

In addition to high initial costs, new NPPs include investment risks that, while not unique to nuclear energy, are nonetheless significant. There is completion risk (that the plant will never be finished and never generate revenues to repay the investment), regulatory risk (that approved requirements might change in midstream) and political risk (that government policies affecting the profitability or even the desirability of nuclear power may change). All of these can affect a power generator's credit rating and require a higher return on investment to justify risks associated with such longer payback periods. OECD investment rules already add a 1% risk premium to lending rates on all OECD export credits to developing countries where nuclear power plants are concerned. A major uncertainty for nuclear power is thus whether future market prices will permit nuclear owners to afford such premiums and still turn a profit.

The generating cost ranges presented in Table II-3 are subject to different sensitivities. Because of high capital costs and long lead times, nuclear power costs are highly sensitive to interest rates. Coal plant capital costs vary greatly with the pollution abatement schemes required. Gas generation costs are highly sensitive to gas prices, which are a relatively high proportion of total costs. Thus the inclusion of nuclear power in a utility's generating mix can be a useful hedge against fuel price and exchange rate volatility.

II-2.3.3. Looking to the Future

The future of nuclear power will depend to a large extent on continually improving the economic competitiveness of new nuclear power plants in the global market. Benchmark targets will constantly move as competing technologies steadily improve their own performance and costs. Success for nuclear energy will depend partly on factors over which the nuclear industry has control, and partly on factors outside its control. Among the latter are fossil fuel prices, the priority given to energy supply security, restrictions on greenhouse gas emissions, growth in energy demand, regulatory uncertainties and innovations and the political will to move ahead on waste disposal.

The key factors over which the nuclear industry has substantial control are innovation, cost control and commercial risk reduction, which usually translate into shorter construction times, lower capital costs, and enhanced safety and proliferation resistance. The next section describes the status and prospects of efforts currently underway.

Table II-3: Capital costs, generating costs and construction times for different electricity generating options. Based on Refs [10] and [13].

| | Cost per kW(e) installed US \$ ^{a)} | Total cost for 1 000 MW capacity Billion US \$ | Construction period Years | Typical plant size MW | Typical plant turn key costs Billion US \$ | Indicative generating costs ^{b)} US c/kWh |
|------------------------|--|--|---------------------------|-----------------------|--|--|
| Nuclear LWR | 2 100 – 3 100 | 2.1 – 3.1 | 6 – 8 | 600 – 1 750 | 1.5 – 4.2 | 4.9 – 6.8 |
| Nuclear, best practice | 1 700 – 2 100 | 1.7 – 2.1 | 4 – 6 | 800 – 1 000 | 1.3 – 2.1 | 4.0 – 4.7 |
| Coal, pulverized, ESP | 1 000 – 1 300 | 1.0 – 1.3 | 3 – 5 | 400 – 1 000 | 0.5 – 1.3 | 3.2 – 4.5 |
| Coal, FGD, ESP, SCR | 1 300 – 2 500 | 1.3 – 2.5 | 4 – 5 | 400 – 1 000 | 0.6 – 2.5 | 3.6 – 6.3 |
| Natural gas CCGT | 450 – 900 | 0.45 – 0.9 | 1.5 – 3 | 250 – 750 | 0.2 – 0.6 | 2.6 – 4.8 |
| Wind farm | 900 – 1 900 | 0.9 – 1.9 | 0.4 | 20 – 100 | 0.03 – 0.12 | 3.5 – 9.2 |

ESP = electrostatic precipitator; FGD = flue gas desulphurization; SCR = selective catalytic reduction; CCGT = combined cycle gas turbine; GJ = gigajoule.

^{a)} Including interest during construction

^{b)} Based on 10% discount rate, 20-year planning horizon and fuel costs ranging from \$1/GJ to \$2/GJ for coal and \$1/GJ to \$5/GJ for natural gas. Wind generating costs depend on mean wind speeds and availability factors.

II-2.4. Advanced Designs

In competitive markets, technologies must improve and innovate or be left behind. This section summarizes the principal current directions in advanced reactor designs⁵.

II-2.4.1. Evolutionary Water-Cooled Reactors

Light water reactors

In 1998, Framatome ANP in France and Germany completed the basic design for a 1 545 MW(e) European pressurized water reactor. The relatively high power level was chosen to capture economies of scale. Together with partners from Finland, the Netherlands, Switzerland and France, Framatome ANP in Germany is also developing the basic design of the SWR-1000, an advanced BWR with passive safety features.

⁵ An “advanced design” is a design of current interest for which improvement over its predecessors and/or existing designs is expected. Advanced designs include both evolutionary designs and innovative designs. An innovative design incorporates radical conceptual changes in design approaches or system configuration. Substantial R&D, feasibility tests and a prototype or demonstration plant are probably required.

In Sweden, Westinghouse Atom is developing the 1 500 MW(e) BWR 90+, an advanced boiling water reactor with improved safety and operability.

Japan is achieving the benefits of standardization and series construction in the case of its ABWR units⁶. Future ABWR costs are expected to decline significantly through standardization, design adjustments based on experience and improved project management. Development began in 1991 on the 1 700 MW(e) ABWR-II to capture further economies-of-scale. The first ABWR-II is expected to be commissioned in the late 2010s. Mitsubishi Heavy Industries and Westinghouse have completed the basic design for a 1 530 MW(e) advanced PWR for the Japan Atomic Power Company's Tsuruga-3 and -4.

In the Republic of Korea, the benefits of standardization and series construction are being realized with the 1 000 MW(e) Korean Standard Nuclear Plants (KSNPs)⁷. Korea Electric Power Corporation (KEPCO) is developing the improved KSNP⁺ and, since 1992, the Korean Next Generation Reactor, now renamed the Advanced Power Reactor 1400 (APR-1400). The 1 400 MW(e) power level was selected to capture economies of scale. In March 2001, KEPCO started the Shin-kori-3 and -4 project for the APR-1400.

In the USA, designs for a large advanced PWR (the Combustion Engineering System 80+) and a large BWR (General Electric's ABWR) were certified in May 1997. Westinghouse's mid-size AP-600 design with passive safety systems was certified in December 1999. Westinghouse is currently developing a 1 090 MW(e) plant called the AP-1000 that uses passive safety technology developed for the AP-600 with the goal of capturing additional economies of scale. General Electric is designing a 1 380 MW(e) European simplified BWR applying economies of scale together with modular passive safety systems. The design draws on technology features from General Electric's ABWR and from their earlier 670 MW(e) simplified BWR with passive systems.

In the Russian Federation, efforts continue on evolutionary versions of the current WWER-1000 (V-320). These include the WWER-1000 (V-392) design, of which two units are planned at Novovoronezh, and WWER-1000 units planned in China, India and the Islamic Republic of Iran. A medium-power WWER-640 unit with passive safety systems has been developed, and development has begun on a high-power WWER-1500.

The China National Nuclear Corporation is developing the CNP-1000 plant. China is pursuing self-reliance both in designing the plant and in fostering local equipment manufacture with the objective of reducing construction and operation costs.

Heavy water reactors

In Canada, Atomic Energy of Canada Limited's development of the next generation CANDU plants (NG-CANDU) retains the present evolutionary CANDU reactor characteristics and power levels (e.g. the 650 MW(e) CANDU-6 and 900 MW(e) CANDU-9

⁶ The first two ABWRs in Japan, the 1 360 MW(e) Kashiwazaki Kariwa-6 and -7, have been in commercial operation since 1996 and 1997 respectively. ABWR plants are under construction at Hamaoka-5 and Shika-2, and undergoing licensing at Ohma-1. Another eight ABWRs are in the planning stage.

⁷ The first two KSNPs, Ulchin-3 and -4, have been in commercial operation since 1998 and 1999 respectively, and four more units (Yonggwang-5 and -6 and Ulchin-5 and -6) are under construction.

with horizontal fuel channels and on-line refuelling). New features include a fuel-bundle design based on slightly enriched uranium and light water coolant.

In 2000, India began construction on two units, each with a net capacity of 490 MW(e), at Tarapur that incorporate feedback from the country's indigenously designed 202 MW(e) units.

II-2.4.2. Innovative Water-Cooled, Gas-Cooled and Liquid-Metal-Cooled Reactors

The principal objectives of many innovative designs are short construction and startup times and low capital costs. Several innovative designs are in the small-to-medium sized range and would be constructed with factory built structures and components, including complete modular units for fast on-site installation. Small-to-medium sized reactors could also reap benefits from economies of series production, in contrast to the economies of scale sought by larger designs. They may also be easier to finance and attractive to countries with small electricity grids or remote locations. Finally, they may be more appropriate for non-electric applications such as district heating, desalination, hydrogen production and oil production from tar sands and heavy crudes.

Water-cooled reactors

For small-to-medium sized light water reactors, the design trend has been towards long core life and modular design for factory production of standardized components and systems. Several "integral" PWR designs eliminate primary system piping by housing the steam generator in the same vessel as the reactor core. A Westinghouse-led international team is developing the modular, integral IRIS design (100-300 MW(e)) with an eight-year reload core life and maintenance requirements only once every four years. Argentina's CAREM reactor (prototype design of 27 MW(e)) is cooled by natural circulation and has passive safety systems. The Republic of Korea's 330 MW(th) SMART design is an integral PWR and, like CAREM, uses no soluble boron. The next step is the construction of a 65 MW(th) SMART pilot plant.

The Japan Atomic Energy Research Institute is developing an extension of the MRX ship reactor design, which is an integral design of up to 300 MW(e). The Toshiba Corporation and the Tokyo Institute of Technology are developing a long operating cycle simplified BWR, which is cooled by natural circulation and has passive safety systems. It is a 100-300 MW(e) design. Their target is a 15-year core life.

Russia has developed a 600 MW(e) integral PWR design and several small reactor designs including the barge-mounted 35 MW(e) KLT-40C, a loop-type PWR; RUTA-55, a pool-type PWR; UNITHERM, a 15 MW(th) PWR with a 20-year single core life; ABV-6, a 6 MW(e) integral PWR based on marine technologies and VK-300 a scaled-up BWR from their VK-50 plant.

In China, the Institute for Nuclear Energy Technology near Beijing has developed a 200 MW(th) integral PWR, called the NHR-200, for desalination and district heat.

In Europe, seven partners are assessing the feasibility of a high-performance LWR operating thermodynamically in the supercritical regime. Thermodynamically supercritical concepts are also being pursued in Japan and the USA. Thermal efficiencies of 40-45% are projected with simplified plant designs.

Also, in Canada, AECL is developing an innovative design, the CANDU-X, which would use supercritical coolant to achieve high thermodynamic efficiency.

India is developing the Advanced Heavy Water Reactor, a 235 MW(e) heavy-water-moderated, boiling-light-water-cooled, vertical-pressure-tube-type reactor, with passive features, and optimized to use thorium fuel for power generation. The conceptual design and the design feasibility studies are complete. The reactor is now in the detailed design stage.

Gas-cooled reactors

Modular high-temperature gas-cooled reactors with coated particle fuel, inherent safety features and passive systems, coupled with state-of-the-art power conversion technology have sparked renewed interest. They can be used for more efficient electricity generation, co-generation of electricity and heat and high-temperature applications. Designs take advantage of high heat capacities, negative temperature coefficients of reactivity and high retention of fission products within the coated fuel particles at accident conditions. They incorporate passive systems for removing decay heat based on natural convection and heat radiation.

In China, the 10 MW(th) pebble-bed high-temperature reactor (HTR-10) at Tsinghua University achieved criticality in December 2000. It will be used to gain experience and conduct experimental and safety demonstration testing. Initial operation will be with a steam turbine, with prospects for later conversion to a gas turbine. Benchmark experiments in reactor physics are being conducted in conjunction with the IAEA.

In Japan, the 30 MW(th) High Temperature Engineering Test Reactor continued power ascension operation during 2001, reaching 20 MW(th) in February and full power (30 MW(th)) in December. Benchmark experiments in reactor physics and thermal hydraulics are being conducted in conjunction with the IAEA. A 600 MW(th) gas turbine design for electricity production is under development.

The Russian Federation Ministry of Atomic Energy and the US Department of Energy are designing a gas turbine modular helium reactor (GT-MHR). The draft design was prepared in December 2001. Such a design is seen as one possibility for using weapons grade plutonium for electricity and heat production with increased inherent safety and economic efficiency. There are plans to construct a 300 MW(e) GT-MHR and a plutonium fuel fabrication facility on the site of the Siberian chemical complex in Seversk by 2010. In the USA, a Utility Advisory Board including companies accounting for 35% of US nuclear electricity production has been set up to help promote the GT-MHR project. Also participating are Tepco in Japan and the Russian State Concern for the Production of Electrical and Thermal Energy at Nuclear Power Plants (Rosenergoatom).

Eskom, South Africa's Industrial Development Corporation and BNFL (United Kingdom) are jointly developing a direct-cycle gas turbine pebble bed modular reactor (PBMR) for more efficient generation of electricity with a high degree of safety achieved by inherent features and passive safety systems. At the end of 2001 the PBMR design was in the detailed engineering stage that precedes completion of the final design, and investors have indicated that they expect to make a decision by the end of 2002 on whether to build a demonstration plant in South Africa.

Liquid-metal-cooled reactors

Owing to increasingly available low-cost uranium, development objectives for liquid-metal-cooled reactors now include incinerating plutonium stocks and partitioning and transmutation. Research is underway in several countries on both fast reactors (China, France, India, Japan and Republic of Korea) and hybrid systems such as accelerator-driven systems and fusion/fission hybrids (China, India, Japan, Republic of Korea, European Union, Belarus, Russian Federation and the USA). The potential advantages of accelerator driven systems (ADS) are low waste production, high transmutation capability, enhanced safety characteristics and better long-term utilization of resources (e.g. with thorium fuels). Common goals of current R&D programmes are lower costs, improved efficiency, enhanced safety and proliferation resistance, and a simplified nuclear fuel cycle.

In China, the 25 MW(e) Chinese Experimental Fast Reactor is under construction. First criticality is scheduled for the end of 2005.

Japan considers the prototype fast breeder reactor MONJU the cornerstone for R&D activities, and is making a considerable effort to restart it. The Japan Nuclear Cycle Development Institute's ongoing feasibility study on a commercialized fast reactor cycle system examines reactor types, fuel fabrication technologies, and spent fuel reprocessing methods, with the objective of converging on a cost-competitive fast breeder cycle technology and comprehensive R&D programme.

The Republic of Korea is developing both the fast reactor KALIMER and the accelerator-driven system HYPER project (Hybrid Power Extraction Reactor). The conceptual and basic designs of KALIMER will be completed by 2002 and 2006 respectively. The first phase of the HYPER project was completed in 2000, with a project peer review scheduled for 2003 and initial fuel irradiation studies targeted around 2005.

India is doing the detailed design, R&D, manufacturing technology development and safety review for the 500 MW(e) Prototype Fast Breeder Reactor (PFBR), focusing on reactor physics, engineering development, safety engineering, structural mechanics, thermal hydraulics, metallurgy, non-destructive evaluation, chemistry and reprocessing.

The Commissariat à l'énergie atomique in France has launched an R&D programme to study promising technologies, using as a reference concept a gas-cooled fast reactor with an on-site closed fuel cycle. In the United Kingdom, BNFL is examining core design, thermal-hydraulics design and fuel design for gas-cooled fast reactors and for accelerator-driven systems. The European Organization for Nuclear Research and the European Commission's Joint Research Centre are supporting ADS studies in eight countries.

By 2010, Russia plans to complete the construction work on the BN-800 fast reactor at the Beloyarsky nuclear power plant site. Apart from BR-10, BOR-60 and BN-600 reactor lifetime extension justification work, and BN-600 hybrid core design studies, Russia's fast reactor R&D concentrates on advanced concepts with enhanced safety features. Included are a high-power (~1600-1800 MW(e)) sodium-cooled fast reactor, and designs with alternative coolants: lead or lead-bismuth. New technology, known as BREST, is being developed based on fast reactors and a fuel cycle designed to reduce waste and be inherently safe within the site boundary, economically competitive and proliferation resistant. BREST, which has been under development for over a decade, uses a uranium-plutonium nitride fuel and heavy liquid metal coolant (lead). To date, the technical design for the BREST-OD-300 reactor has been elaborated, along with an R&D programme to substantiate the technical design incorporating an on-site fuel cycle. Modular nuclear power plant designs (SVBR-75/100) based on fast reactors cooled by lead-bismuth eutectic (a coolant technology originally developed in Russia for nuclear submarines) are also being investigated. Power plants with SVBR-75/100 reactors could be used for electricity production, heating, desalination or the utilization and transmutation of actinides.

Russia's work on ADS includes design studies and research on basic physical processes.

The US fast reactor and ADS programmes include the experimental breeder reactor EBR-II electrometallurgical treatment programme, the Nuclear Energy Research Initiative (NERI) and the Advanced Accelerators Applications Program (AAA Program). The EBR-II electrometallurgical treatment programme is presently processing about 25 tonnes of EBR-II spent fuel with later R&D planned to improve processing rates and to qualify the waste for repository acceptance. A NERI initiative is developing a 50 MW(e) modular design with lead-bismuth coolant, called the Encapsulated Nuclear Heat Source Reactor, which has a 15-year core life. The AAA Program includes a 10-year R&D plan to define key technologies for transmuting nuclear waste (plutonium, minor actinides and long-lived fission products) and for building the Accelerator-Driven Test Facility (ADTF). The ADTF will serve as the principal test station for proof of performance tests, to demonstrate the safety and operation of accelerator-driven systems, and the efficient transmutation and recycling of minor actinides and long-lived fission products.

International Projects on Innovative Reactors and Fuel Cycles

There are two major international efforts on innovative reactor designs. The Generation IV International Forum (GIF) was initiated by the USA in 2000. Members are Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, United Kingdom and the USA. 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 GIF's goal is to identify, assess, and develop sustainable nuclear energy technologies that can be licensed, constructed, and operated to provide competitively priced energy while satisfactorily addressing nuclear safety, waste, proliferation resistance and public perception concerns in the countries in which they are deployed. A first step is the development of a "technology roadmap" to guide research and development. The roadmap will evaluate all reasonable concepts, including nuclear energy systems for non-electric applications. The end product

will be one or more next-generation nuclear energy systems designed and deployable in most world markets before 2030.

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is based on an IAEA General Conference resolution in September 2000 inviting all interested Member States, both technology suppliers and technology users, to consider jointly international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles. In a subsequent resolution at the 2001 IAEA General Conference, Member States praised INPRO's initial progress and reinforced their strong support for the project. Additional endorsement came in the UN General Assembly resolution on the Report of the IAEA (A/RES/56/94), adopted on 14 December 2001, that emphasized "the unique role that the Agency can play in developing user requirements and in addressing safeguards, safety and environmental questions for innovative reactors and their fuel cycles" and stressed "the need for international collaboration in the development of innovative nuclear technology".

INPRO is an Agency-wide project involving all relevant IAEA departments. It currently has 13 members (Argentina, Brazil, Canada, China, Germany, India, Russian Federation, Republic of Korea, Spain, Switzerland, the Netherlands, Turkey and the European Commission). Seventeen cost-free experts have been nominated by participating countries.

INPRO's Terms of Reference were established at a meeting of senior officials from 25 Member States and international organizations in November 2000. A Steering Committee, composed of members (participants from countries providing extra-budgetary resources) and observers from interested Member States and international organizations, was established to provide overall guidance, advise on planning and methods of work and review results. The Steering Committee met first in May 2001 to review and approve the project's organizational structure, the outline of the proposed report, resources, the overall schedule, the workplan and task contents. The second and third meetings of the Steering Committee, in December 2001 and May 2002, reviewed initial progress reports and approved continued development of the project. They included observers from 12 countries – Australia, Belarus, Belgium, Chile, Croatia, Czech Republic, France, Italy, Japan, South Africa, United Kingdom and USA – and from four international organizations: the International Institute for Applied Systems Analysis, the International Science and Technology Center, the International Energy Agency and the Nuclear Energy Agency of the OECD. The meetings also focused on mechanisms and criteria to strengthen direct scientific input into the project from both member and observer countries and organizations and on preparations for the Phase 1A report.

The project's overall objectives are to ensure that nuclear energy is available to help meet 21st century energy needs and contribute to sustainable development; to engage both technology holders and technology users; and to promote innovations in nuclear reactors and fuel cycles to meet likely future requirements in terms of economics, safety, environmental impacts, proliferation resistance and public acceptance. The current focus (Phase 1A) is on defining such "user requirements", which can then be used by the project or others to help design R&D strategies targeted on anticipated needs in mid-century. INPRO is now developing user requirements in five areas: economics and resources, safety, environmental impacts, proliferation resistance and "cross-cutting issues", which include infrastructural

requirements, industrial requirements, legal and institutional requirements, as well as education, training and R&D implications and socio-political implications. A sixth task will develop assessment methods and criteria for applying these user requirements to specific innovative nuclear designs. Phase 1A is due to be completed in 2002. In Phase 1B, which will start after Phase 1A is complete, Member States will examine innovative designs against Phase 1A's criteria and requirements.

II-2.5. Spent Fuel and Radioactive Waste

II-2.5.1. Spent Fuel

Spent fuel has been safely stored for decades at reactors and interim storage sites. The most recent interim storage site to open is at Zwiilag in Switzerland, which received its first shipment in July 2001. With some modest expansion in storage, these on-site and interim facilities can provide needed storage for many years, allowing time to thoroughly work out the publicly preferred long-term solution. Currently, there is a continuing need for new away-from-reactor spent fuel storage capacity. To reduce fuel cycle costs and spent fuel volumes, more utilities are using more highly enriched fuel leading to higher burnup and smaller reload batches. While this reduces the amount of spent fuel, higher burnup requires longer storage periods prior to disposal. Also, the wait-and-see strategy adopted by many countries for spent fuel means longer – more open-ended – storage periods. Therefore, the lifetimes of existing storage facilities need be extended and new facilities for long-term storage will have to be built.

Although experience has shown that current spent fuel storage technologies provide adequate public health and environmental protection, there will always be opportunities for improvements as technology advances and experience accumulates, and the nuclear safety culture calls for continuous assessment and improvement. This is particularly important for spent fuel storage, given that much spent fuel will be stored longer than was originally envisaged.

To date, the nuclear industry worldwide has accumulated 50 years of storage operating experience based mainly on wet storage systems, which represent a mature and effective technology. Over the past 20 years, the industry has also developed dry storage, which, while still evolving, can now also be considered an established technology. Besides re-racking existing storage pools, dry storage is now generally the preferred technology throughout the world for adding storage capacity. Between October 2000 and September 2001, new dry storage facilities went into operation in Armenia, Switzerland, Ukraine and the USA. Additional dry storage capacity is under construction in Canada, Germany, Hungary, Spain, Ukraine and the USA. In Argentina, Czech Republic, Germany, Italy, Romania, Russia and the USA, additional dry storage capacity is in the planning or licensing stage.

COGEMA, the French fuel reprocessor, and Electricité de France signed a new reprocessing contract on 30 August 2001 covering the backend of much of the French fuel cycle for the next seven years.

Two additional important recent developments include, first, a new Russian law approved in July 2001, which makes the import of spent nuclear fuel for indefinite storage

and/or reprocessing possible. This raises the possibility of regional or international spent fuel storage facilities and/or geological disposal facilities – possibilities that could have comparative advantages from both safety and efficiency perspectives. Second is the entry into force in June 2001 of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The Convention, ratified by 27 Member States as of December 2001, subjects national radioactive waste management practices to international peer review. Among other things, this will make radioactive waste management more publicly transparent, thereby contributing, it is hoped, to improved public and political acceptance of radioactive waste management facilities.

II-2.5.2. Radioactive Waste

Most nuclear waste is low and intermediate level waste (LILW) – see Fig. II-5. Although LILW facilities have operated in many countries for decades, some countries (e.g. Belgium, Hungary and the Republic of Korea) have had difficulties siting LILW disposal facilities.

The amount of LILW is projected to increase significantly in the next few decades owing to the growing number of reactors due to be decommissioned. As of December 2000, there were 93 commercial NPPs in 16 countries in some phase of decommissioning, and the IEA estimates that total NPP retirements for 1997-2020 will be 135. The NPPs that have been closed early have been generally smaller than average. Future retirements can thus be expected to generate greater LILW volumes.

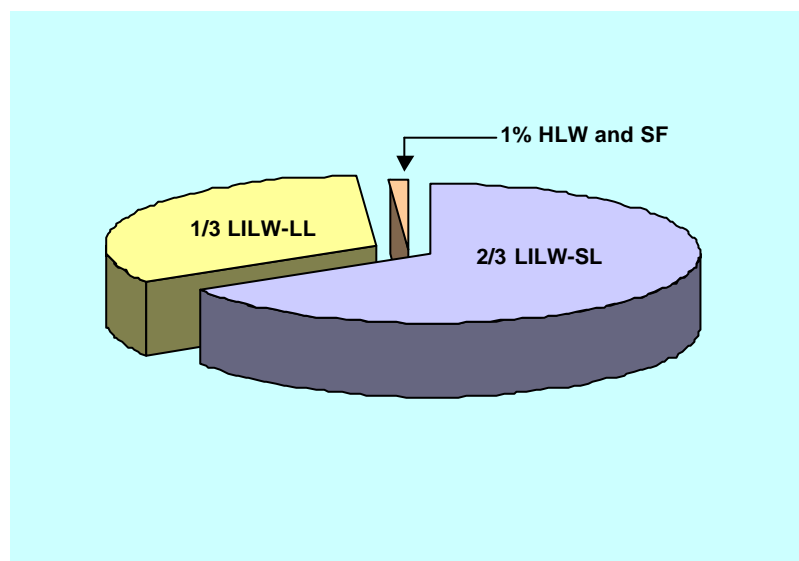


Figure II-5. Distribution, by volume, of waste in the European Union (HLW = high level waste; SF = spent fuel; LILW-LL = low and intermediate level waste – long-lived; LILW-SL = low and intermediate level waste – short-lived)

II-2.5.3. High Level Waste

The major political and public acceptance issue today is the disposal of spent fuel and HLW. The preferred approach in most countries is geologic disposal using both natural and

engineered barriers to isolate the wastes for many thousands of years. Countries have taken a range of approaches to identifying potential sites. In Sweden two of six original candidate communities have been selected for, and have agreed to, detailed geological investigations. These should begin in 2002 and run for five or six years. The Swedish nuclear fuel and waste management company, SKB, hopes to make a final site proposal by about 2007. In December 2000, the Finnish Government approved an application for a decision “in principle” filed by Posiva, the nuclear waste company, to build a final repository for spent fuel in a cavern near the nuclear power plants at Olkiluoto. The Parliament ratified the decision in May 2001. In addition, separate construction and operating licences, issued by the Government, will be required. Construction would start in 2011 and operation about ten years later. In May 2002, when Parliament ratified the decision in principle for a fifth Finnish NPP, it also ratified a separate decision in principle so that spent fuel from the new reactor could also be deposited at Olkiluoto.

In the USA, the Waste Isolation Pilot Plant (WIPP) began receiving military transuranic waste for permanent disposal in 1999. In May 2001, the Department of Energy (DOE) determined that the proposed Yucca Mountain disposal site meets the radiation standards set by the Environmental Protection Agency earlier in the year – 15 mrem (0.15 mSv) per year at the site boundary for 10 000 years, of which no more than 4 mrem (0.04 mSv) per year may come from groundwater. (For comparison, average natural background radiation in the USA is about 300 mrem (3 mSv) per year.) In February 2002 President Bush approved proceeding with Yucca Mountain. The State of Nevada formally objected. Congress must explicitly override their objection by July 27. The House of Representatives voted to do so in May. The Senate has yet to vote.

II-2.5.4. Demonstrating Geologic Disposal

Countries currently developing geologic repositories for HLW disposal have generally adopted a stepwise approach that includes a period of intensive underground investigations and testing. Table II-4 provides a list of the principal existing underground research facilities.

Since it is expensive and time-consuming to develop such facilities, the Governments of Canada and Belgium have offered to make their underground research facilities available to the IAEA as international demonstration and training centres for scientists from Member States with limited resources. The Agency convened a meeting to define the scope of the project in October 2001. There was substantial interest, particularly among Member States with less developed geological disposal programmes, and a research network is being established to provide assistance in early phases of programme development, such as technologies for site characterization, site selection criteria, overall performance assessment and concept assessment.

Research continues on reducing waste volumes through new techniques to reduce actinide generation and to transmute long-lived radioactive wastes. Research also continues on methods of retrieving wastes from geological repositories after emplacement. The relative merits of permanent versus retrievable disposition constitute an ongoing political discussion, and different countries may ultimately weigh them differently. Retrievable disposition offers the possibility of being more responsive to future changes in technology and social

preferences. Permanent disposition can reduce requirements for active management and safeguards.

Table II-4. Main underground research facilities (information compiled by consultants at an IAEA sponsored meeting in 1999)*

| COUNTRY | LOCATION | USUAL NAME/TYPE OF FACILITY | HOST ROCK/FORMATION | TIME PERIOD |
|-------------|----------------------------------|-------------------------------|---------------------|----------------------------|
| BELGIUM | MOL | HADES+URF PRACLAY | Plastic clay | since 1980 |
| CANADA | LAC DU BONNET Manitoba | URL | Granite | since 1984 |
| FINLAND | OLKILUOTO (in VLJ repository) | Research Tunnel | Granite | since 1993 |
| FRANCE | FANAY Augères/Tenelles | Galleries in U Mines | Granite | 1980-1990 |
| | AMELIE | Galleries in K Mine | Bedded salt | 1986-1994 |
| | TOURNEMIRE | Test Galleries | Shale | since 1990 |
| GERMANY | ASSE | Test Galleries in K/salt mine | Dome salt | 1977-1995 |
| | GORLEBEN | URL | Dome salt | since 1997 (now halted) |
| | KONRAD | Test Galleries in Fe Mine | Shale | since 1980 |
| JAPAN | TONO | Galleries in U Mine | Sandstone | since 1986 |
| | KAMAISHI | Galleries in Fe-Cu Mine | Granite | 1988-1998 |
| SWEDEN | STRIPA | Galleries in Fe Mine | Granite | 1976-1992 |
| | ÅSPÖ | HRL | Granite | since 1990 |
| SWITZERLAND | GRIMSEL | GTS at dam tunnel | Granite | since 1983 |
| | MONT TERRI | Galleries at road tunnel | Shale | since 1995 |
| USA | NEVADA Test Site | CLIMAX | Granite | 1978-1983 |
| | NEVADA Test Site | "G-Tunnel" | Tuffs | 1979-1990 |
| | CARLSBAD | WIPP | Bedded salt | since 1982 |
| | YUCCA Mtn. | ESF | Tuffs | since 1993 |
| | YUCCA Mtn. | Busted Butte | Tuffs | since 1997 |

* Existing facilities where tests were and/or are still undertaken.

PART III

APPLICATIONS FOR FOOD, WATER AND HEALTH

III-1. SUSTAINABLE AGRICULTURE AND FOOD SAFETY

III-1.1. Crop Improvement

The application of gamma rays, X-rays, fast neutrons and chemicals in breeding programmes has led to the development of new crop varieties with improved agronomic traits, yield, quality and tolerance to abiotic and biotic stresses. Breeding programmes for genetic improvement using mutation techniques have been initiated to solve production or quality problems for traditional crops such as teff, amaranth, noug, Bambara groundnut, lupin, grass pea and cocoyam. With recent advances in the sequencing of genomes and gene identification, the next challenge is to assign functions to the genes. Chemical, radiation and transposon mutagenesis are the most versatile tools for assessing gene function in order to facilitate the breeding process.

Nuclear-based techniques are also used in agriculture to provide unique and quantitative data on rates of soil processes and help evaluate methods of solving soil problems. One example is a technique based on the fallout radionuclide caesium-137 that is being used to obtain spatially and time-integrated estimates of erosion rates in order to evaluate the efficacy of soil conservation measures.

In many countries, the stable isotope nitrogen-15 is also being used to identify efficient legume inoculants and legume genotypes; to assess the value of organic residues as sources of nitrogen for crops; and to monitor the movement of fertilizer-derived nitrate to surface water and groundwaters. The radioactive isotope phosphorus-32 is being used in a similar way to evaluate the reactivity of different sources of phosphate rocks as fertilizer materials, and to identify crop varieties or genotypes that are efficient in scavenging tightly-held phosphorus from acidic tropical soils. The stable isotope carbon-13 is being used to gather specific information on the rates of sequestration of carbon from crop residues and the simultaneous losses of native carbon, adding a new dimension to the understanding of carbon dynamics and balance in diverse cropping and tillage systems and agroecological zones

The sterile insect technique (SIT), which involves the large-scale production and systematic release of gamma-radiation-sterilized insects of a pest population, is an environment-friendly method of pest control that has proved highly effective in reducing insecticide use against several key insect pests. The mass production capacity for sterile fruit flies, notorious pests of major economic importance and quarantine significance, is increasing rapidly (Fig. III-1). SIT technology to suppress, contain or eradicate these insect pests has been more widely applied in recent years following the first successful large SIT programme to prevent the spread of the Mediterranean fruit fly (medfly) into Mexico. Similarly successful fruit fly programmes have been implemented in Australia, Argentina, Chile, Japan and the USA.

The use of male-only strains for medfly SIT is now the norm for this technology. Improved strains with higher production and increased stability that are molecularly marked are

now available. These genetic sexing strains have enabled fly production facilities and plant protection authorities to produce and release only sterile male insects, resulting in reduced rearing costs and greater effectiveness of released flies. This in turn has allowed the application of SIT to suppress fruit fly pests as an insecticide replacement rather than only as an eradication tool. The feasibility of this approach has been confirmed through pilot SIT suppression projects in various countries, including Israel, Jordan, Philippines, South Africa and Thailand. Similar integrated suppression projects are now being initiated in several Central American and Mediterranean Basin countries. SIT for major moth pests is under development, and operational projects are in progress against the apple codling moth in Canada and the cotton pink bollworm in the USA.

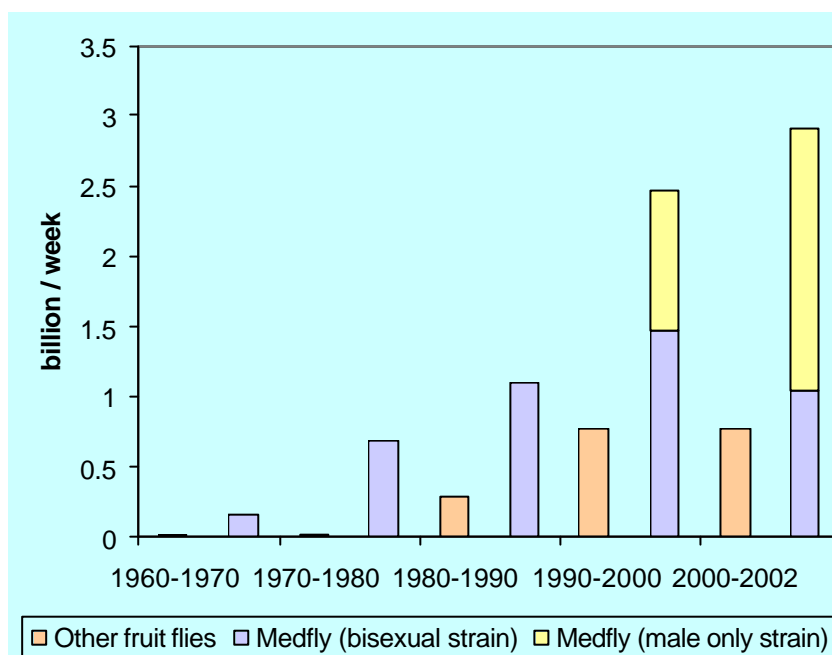


Figure III-1. Current worldwide production capacity of sterile fruit flies.

The economic benefits from SIT are significant. Maintaining Mexico free of medfly at an annual cost of approximately \$10 million has protected fruit and vegetable export markets of over \$1 billion/year. The eradication of the medfly from Chile in 1995 is estimated to have resulted in potential markets for fresh fruit exports of up to \$500 million per year. SIT suppression programmes have been effective in reducing insecticide applications and fruit losses, as well as rejections due to pest presence in fresh fruit exports, thus representing significant savings and environmental benefits. In Israel, for example, medfly suppression using SIT has already resulted in annual exports of peppers and tomatoes valued at \$5 million.

As for crop mutation for improved production, during the last decade, the world of pure genetics has entered a new age of genomics – the study of all genes and their function. A great deal of DNA sequence information is available now, in particular from rice and Arabidopsis. However, the functions of the derived genes are mostly unknown. Concentrated research efforts are directed towards filling this so-called “phenotypic gap”.

This has led to a reinforced demand for mutagenized plant material. Mutation induction using nuclear techniques plays an important role in generating the desired mutant populations. Recent reports on the homology of genes and gene order between for instance the grass genomes (synteny) suggest that the knowledge acquired will also be useful for the identification and isolation of genes from under-utilized crops. The distribution of material will help make valuable crop mutants available for plant breeders and geneticists around the world in locations other than where they have been produced.

Towards more efficient land use, the development, refinement and calibration of caesium-137 techniques have provided a universal tool to quantify soil redistribution rates in a range of natural and agroecosystems. However, the limiting factor in the methodology is low levels of caesium-137 inventories, and therefore the acquisition of modern counting equipment by developing country institutions will be key to the wider application of the methodology. Further research and development on the combined use of caesium-137 and other fallout radionuclides such as lead-210 and beryllium-7 is required to assess both long- and short-term erosion and sedimentation rates.

The potential to expand the current applications of SIT and to develop the technology further to facilitate applications against other major insect pests is considerable. SIT is also increasingly being considered as an eradication tool to deal with the rapidly growing problem of incipient outbreaks of exotic invasive species before they become permanently established. Transgenic strains of many insect pests are now available and are being used to develop new methods of control and for improving the efficiency of SIT. One major advantage of transgenic technology could be the ability to use the same molecular method in many different pest species.

III-1.2. Increasing Livestock Productivity

Genetic engineering is now at the forefront of basic, adaptive and applied or near market biological research. At the centre of research on improving livestock productivity or reducing losses from disease, is the use of ^{32}P - and ^{33}P - labelled nucleotides, ^{131}I amino acids and proteins that provide a measurable signal for gene identification and characterization, and for marking in vitro expressed proteins and other biologically active compounds.

The sterile insect technique can be used not only for the control of insect pests, but can also play a major part in fighting livestock disease by controlling the disease-bearing pests. Tsetse fly transmitted trypanosomosis occurs only in Sub-Saharan Africa, where farming is largely carried out without ruminant livestock because of this disease. Significant improvements have been made in the mass production, quality control and sexing of tsetse flies following the application of SIT to eradicate tsetse from Zanzibar in 1996. The improved technology is being applied through a multi-agency effort, and preparations are under way for a number of SIT pilot projects in isolated areas of mainland Africa, most notably in Botswana, Ethiopia and Mali.

Harmonization efforts are under way to control another major livestock pest, myiasis-causing flies (such as the Old World screwworm) that attack livestock and other warm-blooded animals. The Arab Organization for Agricultural Development, the FAO and the IAEA are collaborating in a joint regional feasibility project in the West and South East Asia

regions. SIT is currently being used for the eradication of the New World screwworm in Jamaica and to maintain a sterile fly barrier in Panama, to protect North and Central America, where New World screwworm has already been eradicated.

Future research will focus on widening and deepening the use of the technologies described above. Field use of many of the products may be limited, at least initially, by ethical and ecological considerations and concerns about intellectual property rights, but there is considerable potential for further improving the cost-effectiveness of SIT for screwworm and tsetse eradication, and for expanding the development and use of this technique to help address other insect pests of livestock. The large-scale integrated application of SIT, particularly against tsetse to free significant areas of Sub-Saharan Africa, will depend on public and private ventures to provide the various services required in these eradication programmes.

III-1.3. Food Safety

Food irradiation has emerged as a viable sanitary and phytosanitary treatment for food to meet the requirements set out in the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) and in the Agreement on Technical Barriers to Trade (TBT Agreement) of the World Trade Organization. Currently, over 30 countries use this technology to ensure safety and quality and to satisfy quarantine regulations in trade in some foods, including meat products, fresh fruits, spices and dried vegetable seasonings. Large commercial-scale irradiation of ground meat to ensure microbiological safety started in the USA in mid-2000, and irradiated products were widely sold in more than 2 000 supermarkets in 2001, apparently with no resistance from consumers. Many other countries, especially those in Asia and the Pacific, Latin America, and some Middle East and African countries could benefit immensely from using this technology to reduce post-harvest food losses, control a number of food-borne diseases and facilitate food trade. If the food irradiation industry continues to grow, this will necessitate more widespread capability among producing countries to measure the amount of radiation delivered.

International standards/guidelines and recommendations are being developed/revised by the Codex Alimentarius Commission to ensure the quality and safety of foods, including those processed by irradiation as well as those which may be contaminated by chemical and biological agents. As a result of international collaboration, the electron capture detector is now accepted and is one of the most widely used detectors for food contaminants and for environmental samples. Radiotracer techniques are also used in various analyses for food contaminants to improve speed and precision, resulting in cost savings in terms of reagents.

There will be an increasing need for isotopes and radiation either to process food to ensure its safety and quality or to develop, validate and standardize low-cost analytical methods for food contaminants and residues suitable for developing countries. Emerging problems that affect human health and agricultural trade include risks from veterinary drug residues, including the risks of transferring antibiotic-resistant pathogens from animals to people and mycotoxin contamination in foods. Concerted training, analytical methods (especially radioimmunoassay) and a more co-ordinated response all need strengthening in developing countries.

III-2. WATER RESOURCES

Nuclear energy has two contributions to make to global efforts to expand freshwater resources. First are applications of isotopes in hydrology, using the naturally imparted “isotopic fingerprints” of water to rapidly provide hydrological information for large areas. Second is the potential of nuclear-powered desalination of sea water from the world’s oceans.

The number of laboratories active in isotope hydrology and network stations for monitoring isotopes in precipitation around the world continues to grow. Also growing is the number of papers published in major scientific journals, which suggests the increased use of isotopes in hydrology where isotopes are one of the investigative tools (Fig. III-2). The dominant field of application is related to groundwater, but applications in climate change studies, nearly non-existent in 1960, have grown to nearly the same level.

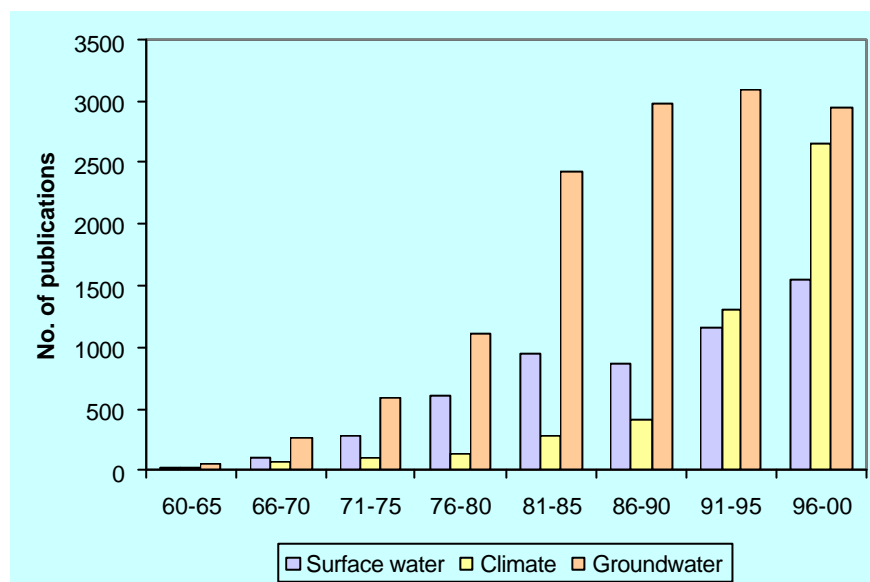


Figure III-2. Growth of isotope hydrology literature

New future applications in isotope hydrology will benefit from steady advances in analytical methods and instrumentation and from the availability of global isotope data. Increased use of highly sensitive accelerator mass spectrometry (AMS) has resulted in a wider use of carbon-14 methods. The AMS analysis of tritium in small sample sizes is being further developed to open up new areas where tritium measurements can be applied.

Viable spectroscopic methods as alternatives to conventional mass spectrometry systems for stable isotope abundance measurement are coming closer to realization. The spectroscopic methods require lower operational skills and less basic infrastructure than mass spectrometers and are likely to greatly increase the access to isotope measuring facilities in many countries.

Turning to nuclear desalination, Japan has accumulated over 100 reactor-years of nuclear-powered desalination. Kazakhstan had accumulated 26 reactor-years before shutting down the Aktau fast reactor at the end of its lifetime in 1999. Interest is driven by the expanding global demand for fresh water, by concern about greenhouse gas emissions and pollution from fossil fuels and by developments in small and medium-sized reactors that might be more suitable for desalination than large power reactors. The IAEA is extending its Power Reactor Information System to accommodate information on more than 50 nuclear power reactors connected with heat application systems including desalination.

Egypt is about to complete a feasibility study of a nuclear co-generation plant (electricity and water) at the El-Dabaa site. France is promoting a joint European study on reactor development for nuclear desalination (the EURODESAL project). In India, civil and engineering work for a 6300 m³/d nuclear desalination demonstration plant at Kalpakkam is under way, with commissioning expected to begin in early 2002. Canada has built a test rig for verifying preheat reverse osmosis process performance. China initiated a pre-feasibility study of a nuclear seawater desalination plant in the Yantai area using an NHR-200. The Republic of Korea is proceeding with the basic design of the SMART concept. Pakistan is continuing its efforts to set up a nuclear desalination demonstration plant, to be connected to the Karachi nuclear power plant. The Russian Federation is working on a floating power unit design and plans to construct a pilot plant in 2005–2006. Tunisia is planning a pre-feasibility study of a customized nuclear desalination plant for specific site conditions.

III-3. HUMAN HEALTH

The most widespread diagnostic applications of ionizing radiation and nuclear techniques are X-ray imaging in diagnostic radiology and the use of radioactive biological tracers in nuclear medicine. The dominant field for the therapeutic application of radiation in health is radiation oncology, which involves the delivery of curative doses of radiation to targeted volumes in patients with cancer, usually from a solid radiation source positioned outside the patient (teletherapy) or inside the patient (brachytherapy). Therapy by systemic administration of radioactive materials (therapy by open radioactive sources) has been used for many years in treating thyroid diseases, but currently many new therapeutic applications with open radioactive sources are emerging. This section also addresses stable isotope methods for the diagnosis and management of malnutrition, a relatively new field of application.

III-3.1. Diagnostic Applications

III-3.1.1. Diagnostic Radiology

Diagnostic radiology was revolutionized in the 1970s by the development of computed tomography, which provided high quality cross-sectional images of the patient. More recent advances in computing technology permit radiologists to overlay X-ray images with those from a variety of other modalities including nuclear magnetic resonance imaging and radionuclide scans so that anatomical and functional information may be properly co-registered. The next major innovation will probably involve digital X-ray imaging using a

new generation of detectors. The advantages of digital versus conventional systems are in image manipulation, storage, remote transmission and possibly cost.

III-3.1.2. Nuclear Medicine

Nuclear Medicine Imaging and Non-imaging Functional Studies

Nuclear medicine imaging and non-imaging functional studies offer diagnostic and research applications of internally administered open sources of radioactivity. They also support therapeutic applications with open radioactive sources (see Section III-3.3). These techniques are used in a broad range of specialties such as oncology, endocrinology, cardiology, neurology and nephrology. Nearly one hundred different standardized nuclear medicine diagnostic and therapeutic procedures are now available.

The trend in most developed countries is that many hospital patients will undergo a nuclear medicine diagnostic or therapeutic procedure since the speciality is established and radionuclide procedures are available for routine day-to-day applications. In the developing world, however, nuclear medicine has yet to be integrated into routine health care systems. In most developing countries it exists in pockets of excellence in big urban areas, while people living in the rural areas have no access to such facilities. The number of gamma cameras in a country is a reasonable indicator of the status of nuclear medicine, and worldwide data for developed countries show 20 gamma cameras per million inhabitants, compared with a figure of 0.8 for developing countries. Such a lack of equipment contributes to the migration of qualified nuclear medical staff to developed countries.

Molecular Nuclear Medicine

Molecular nuclear medicine is an emerging field of applications that deals with imaging of a disease on a cellular or genetic level rather than on a gross level. Recent advances show promise, particularly in the imaging of gene expression. These molecular techniques provide the means to screen active drugs in vivo, image molecular processes and diagnose disease at a pre-symptomatic stage.

Polymerase chain reaction (PCR) is one of the best and most commonly applied examples of in vitro molecular techniques in human health, especially in the field of molecular epidemiology and diagnostics. PCR has found many applications in both basic research and clinical settings. It is used for the diagnosis of leukaemia, infectious diseases such as Chagas' disease, leishmaniosis, hepatitis B and tuberculosis, as well as genetic disorders such as thalassaemia and muscular dystrophy. Direct detection of mutations responsible for drug resistance in malaria and tuberculosis is one of the most important applications of PCR currently under investigation. The technique is extremely sensitive, since, for example, even one abnormal cell in a million can be detected using PCR.

As of August 2001, the US Food and Drug Administration had approved 25 in vitro molecular diagnostic tests – 18 for infectious diseases (e.g. chlamydia, HIV), six for cancers (e.g. leukaemia) and one for Down's syndrome. A recent report entitled *Successful Business Strategies for Companies in the Diagnostics Industry* predicts that one of the largest increases will be in molecular diagnostics [14].

In Vitro Radioimmunoassay

Radioimmunoassay and its related 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.

The world sales revenues for in vitro diagnostic (IVD) products are expected to continue to increase from \$20 billion in 1999 to \$26.5 billion in 2004. Immunoassay constitutes about 10 %, i.e. \$2 to 2.65 billion of IVD revenues. A current medical literature survey shows a moderate decline in the use of radioimmunoassay, with a concomitant rise in techniques which use non-radioactive assays such as enzyme-linked immunosorbent assay (ELISA). However, radioimmunoassay methods are still being used extensively in routine clinical pathological diagnosis in developing countries and even in some high-throughput laboratories of developed countries because of low cost. They are also used fruitfully in developmental work to explore novel methods for patent applications, as well as being an excellent reference standard for verification of non-isotopic assays.

As for future trends, new radiopharmaceuticals in the form of labelled metabolites, oligonucleotides, hormones, enzymes, drugs, receptors and monoclonal antibodies for the early detection and treatment of diseases will continue to be introduced. Besides detection and treatment, nuclear medicine is becoming an increasingly important tool in prognosticating treatment response, determining tissue viability and promoting gene therapy. The application of the surgical gamma probe, which has dramatically changed the concept of managing breast and colon cancer, will continue to expand and play an important role in clinical oncology. Fusion imaging (e.g. fusion of CT/magnetic resonance and nuclear medicine images), with the assistance of newer information and communication tools, will further refine management strategy in a variety of cardiovascular, neurological and oncological conditions.

In the field of molecular nuclear medicine, emerging applications for prognosticating cancer therapy and detecting drug resistance will continue to grow. Future applications may include molecular modelling for designing drugs, gene therapy, evaluating pathogenicity and detecting minimal residual disease.

III-3.2. Therapeutic Applications

III-3.2.1. Teletherapy and Brachytherapy of Cancer

Cancer is a major cause of death in industrialized countries, and the number of cases in developing countries is growing rapidly as life expectancy increases. It is estimated that there were about 10 million new cases of cancer worldwide in 2000, and that these cancers were evenly divided between developed and developing countries. It is projected that in 2015 there will be 15 million new cases of cancer and about 10 million will be in developing countries. Patterns of patient care utilizing radiotherapy differ widely even in the most industrialized countries. For example, in the USA 49% of newly diagnosed cancer patients are treated by radiotherapy, compared to only 15% in Japan [15]. In developed

countries, where cancer management incorporates surgery, radiotherapy and chemotherapy, a cure rate of 45% is achieved.

The most commonly used radiotherapy technique is teletherapy, where the radiation source is placed at a distance from the patient. This has evolved from the use of X-ray tubes to machines where gamma irradiation is derived from ^{60}Co sources. Over the last thirty years, industrialized countries have tended towards the use of linear accelerators to produce beams of electrons and high-energy X-rays. Today teletherapy can be given with great accuracy to conform with even highly irregular tumor shapes simultaneously sparing surrounding healthy tissue (conformal therapy). Brachytherapy, where sources are placed within the body, has also changed over the century of use. Radium has almost completely been replaced by caesium-137 and increasingly by new micro high dose rate iridium-192 sources.

Availability and future need for radiotherapy

The IAEA maintains an international registry of hospitals and clinical institutions that offer radiation therapy using radionuclides or high-energy teletherapy equipment. This database, called Directory of Radiotherapy Centres (DIRAC), includes detailed information on equipment for radiotherapy and brachytherapy, for dosimetry and for treatment planning as well as staff strength and number of patients treated (see Table III-1). Even though developing countries have about 85% of the world population, the developed countries have two-thirds of the world's radiotherapy facilities, 82% of all electron accelerators and over 30% of all cobalt units. Only about 2 200 teletherapy machines, mainly ^{60}Co units, and 850 brachytherapy units are installed in developing countries. Since each machine can be used to treat about 600 patients per year, this gives a capacity of about 1.9 million patients per year. This is far from sufficient to serve the current population, which would require about 2.5 million cancer patients to be treated per year. The current need is for a total of about 4 000 machines, implying a shortfall of about 1 000 machines. As noted above, by 2015, the number of new patients per year in the developing world will total 10 million, with 5 million requiring some form of radiotherapy. A total of about 10 000 machines will be needed to provide treatment for them.

Table III-1: DIRAC data as of August 2001 for global resources in radiotherapy: teletherapy and brachytherapy in developing and developed countries (DIRAC, 2001).

| | Developing | Developed | Total |
|---|-------------|-------------|-------|
| Number of countries | 132 (81%) | 30 (19%) | 162 |
| Radiotherapy centers | 2 327 (44%) | 2 986 (56%) | 5 313 |
| Teletherapy | 2 195 (35%) | 4 097 (65%) | 6 292 |
| Radionuclides: ^{60}Co & ^{137}Cs | 1 424 (69%) | 634 (31%) | 2 058 |
| Accelerators | 771 (18%) | 3 463 (82%) | 4 234 |
| Brachytherapy | 845 (34%) | 1 652 (66%) | 2 497 |

Heavy Particle Radiotherapy

As of July 2001, a worldwide total of 34 440 patients had been treated with different heavy particles. The current trend, for a number of developed countries, has been a steady increase in the number of particle accelerators, predominantly proton accelerators in the 200 to 250 MeV range with the advent of smaller, hospital-based cyclotrons. The most rapid expansion is in the treatment of well-defined tumours particularly cancer of the prostate and chordomas and chondrosarcomas of the base of the skull, where the superior effectiveness of this modality over surgery has been demonstrated. Low-energy cyclotrons (60 to 70 MeV) continue to treat ocular melanomas, a rare tumour of the eye, in competition with surgically attached plaques that contain an array of tiny radioactive seeds or with newer linac photon techniques. There is continuing development of the experimental use of heavy ion therapy (employing helium ions mainly).

III-3.2.2. Therapy with Open Radioactive Sources

The potential of radionuclides for treating certain benign and malignant tumours has been recognized and put to use for the past several decades in the treatment of thyroid cancer, metastatic bone pain, malignant pheochromocytoma and neuroendocrine tumours, liver cancer (hepatocellular carcinoma), and B-cell lymphoma. One new application is the use of iodine-131 Lipiodol or rhenium-188 Lipiodol to treat liver cancer. Liver cancer, or hepatocellular carcinoma, is one of the world's most common malignancies, causing almost one million deaths annually, most of them in developing countries.

Several radionuclide therapeutic procedures are now available for the treatment of benign diseases in addition to cancer, such as hyperthyroidism, coronary artery restenosis, rheumatoid arthritis and haemarthrosis. Iodine-131 therapy has long been accepted worldwide as a safe and effective treatment procedure for hyperthyroidism.

In conjunction with balloon angioplasty to open occluded coronary arteries, there is great interest in the recently introduced intravascular radionuclide therapy using liquid beta-emitting radiopharmaceuticals to prevent restenosis. The procedure is cost-effective, easy to perform, practical and eminently suitable for developing countries.

Radiosynovectomy using beta-emitting radiopharmaceuticals, particularly of the knee joint, offers significant and long-lasting relief from pain and other symptoms in patients with rheumatoid arthritis and haemarthrosis. The procedure is safe, simple and extremely cost-effective in patients suffering from this chronic disease and otherwise requiring long-term treatment with costly analgesics and other medications.

III-3.3. Nutrition

The Commission on the Nutrition Challenges of the 21st Century prepared a report entitled *Ending Malnutrition by 2020: an Agenda for Change in the Millennium* for the UN Subcommittee on Nutrition [16]. This report singles out intrauterine growth retardation (24% of all births), anaemia (2 billion children and adults), vitamin A deficiency (250 million children) and stunting (200 million children) as the most pressing issues in developing countries. It identifies obesity as an emerging epidemic in both developed and developing countries and the health of the elderly as an additional critical issue. Osteoporosis is the most

debilitating disease for the elderly - the World Health Organization reports over 2 million hip/spine fractures per year, mostly in women.

In developed countries, much focus is on obesity and type 2 diabetes, but marginal micro-nutrient malnutrition can be a significant problem in vulnerable groups, i.e. low income groups, single parent families and the elderly. In countries in transition, economics and nutrition go together. With increasing prosperity, the pattern of nutrition-related diseases is changing, but at the same time many of the old problems remain. In least developed countries, the nutrition situation is not improving, with the result that classical protein-calorie malnutrition still exists.

Some of the methods currently used to evaluate the health and nutritional status of subjects can be invasive, inaccurate, unresponsive to small changes and not easily transferred to the field. Nuclear and isotope techniques to complement these alternatives are regarded as essential tools in applied nutrition and research. They have been used extensively in industrialized countries to analyse human energy requirements, body composition including bone mineral density, and the metabolism of important nutrients such as protein, fat, vitamins and minerals. Several strategic applications of isotopic techniques are being introduced in developing countries where they can benefit millions through monitoring improvement in nutritional status, and serve as specific indicators of broader social and economic advances. Practical examples include the following.

- The doubly labelled water method ($^2\text{H}_2^{18}\text{O}$) is the only technique that can accurately determine the energy needs of people in their own environment. The results of investigations on energy expenditure of young children in Cuba and Chile based on doubly labelled water are being used by the FAO/WHO/UNU expert committee convened during 2001 to establish new energy recommendations.
- Methods based on isotope dilution using ^2H or ^{18}O are now widely accepted for monitoring body composition especially in the context of the onset of obesity. Over 2000 subjects from China, India and Nigeria and a few other countries (representing over 40% of the global population) have been investigated to identify changes leading to obesity to formulate preventive care.
- National nutrition interventions based on stable isotope technology have been introduced in Chile and Mexico. In Chile, 300 children participated in a pilot study designed to cover eventually 1.3 million children in a national nutritional intervention programme. As a result, anaemia was reduced from 30% to less than 5% after a year of providing iron-supplemented weaning foods. This has led to use of food fortified in iron and zinc in the national supplementary feeding programme, which is expected to improve educational performance and decrease infections. Mexico has equipped a laboratory with two dedicated mass spectrometers in support of stable isotope technology to assess the effect of food supplements on a large number of pregnant and lactating mothers and to monitor the effect of iron and zinc fortification.
- It is estimated that by 2025 there will be 1.2 billion elderly people in the world. Techniques based on dual energy X-ray absorptiometry offer a non-invasive method for investigating the variation of bone mineral density.

- Persistent diarrhoea accounts for over 60% of infant diarrhoeal deaths in Brazil, 47% in India, 36% in Senegal and 26% in Bangladesh. Stable isotope techniques are the best and most cost-effective methods of diagnosing of *Helicobacter pylori* infection through a simple breath test using carbon-13.
- The Government of Brazil plans to undertake an evaluation of milk distribution programmes using stable isotope technology targeting 2.5 million people. In this first large-scale epidemiological study of its kind, isotopic methods will be employed to measure the body composition of a large number of under-nourished children.

PART IV

APPLICATIONS FOR ENVIRONMENT AND SUSTAINABLE INDUSTRIAL PROCESSES

IV-1. MARINE AND TERRESTRIAL PROTECTION

IV-1.1. Marine Environment

Nuclear applications for marine protection include both studies of the impact of radioactivity in the ocean from nuclear fallout or planned and accidental releases, and the use of such radioactivity as a tracer to better track and understand ocean processes directly, as well as run-off and other marine pollution originating on land.

Isotopic tracer studies of the ocean have helped to determine the circulation patterns and mean residence times of specific water masses, and to estimate mixing coefficients. Begun in the seventies, the Geochemical Ocean Sections Study produced the first comprehensive data set for anthropogenic radionuclides and other isotopic tracers for the Atlantic and the Pacific Oceans. More recently the World Ocean Circulation Experiment generated even higher resolution two- and three-dimensional isotopic (^3H , ^3He , ^{14}C) data, which have been used in studies of the ventilation of the upper waters in the Pacific Ocean, the spreading of intermediate waters in the Pacific and Indian Oceans, and the bottom water circulation in the Pacific Ocean. The oceanic removal and cycling of carbon dioxide, a critical greenhouse gas, is the focus of a recent major international ocean science programme (the Joint Global Ocean Flux Study). The Worldwide Marine Radioactivity Studies co-ordinated research programme provides the most recent and comprehensive information on the levels and distribution of anthropogenic radionuclides, on their time trends, and their mean residence times in the world oceans. More broadly, the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) was adopted in 1995, and the United Nations Environment Programme (UNEP) was tasked to lead the co-ordination effort. Partners in the GPA clearing house system include the IAEA, IMO, FAO, and WHO, together with UNEP. Important considerations are the impact of contaminants such as sewage, persistent organic pollutants, radioactive substances, heavy metals, oils, nutrients, and litter, together with physical alteration and habitat modification.

In addition to anthropogenic radionuclides from global fallout (e.g. ^3H , ^{14}C , ^{90}Sr , ^{137}Cs , ^{239}Pu and ^{240}Pu) that have been widely used as oceanic process tracers, radionuclides discharged from nuclear reprocessing plants at Sellafield and La Hague represent a substantial new tracer signal in the North Atlantic and Arctic Oceans. The distinctive time and composition signatures of these two signals are likely to be of great value in future studies of ocean ventilation rates and routes.

Natural radionuclides (such as lead-210, radium, uranium and thorium isotopes, and others) have also been used as natural tracers of water and sediment dynamics, particle association, transport and fate. For example, indirect measurements of particulate organic carbon flux using $^{234}\text{Th}/^{238}\text{U}$ disequilibria in the water column contribute to a better understanding of environmental change.

Since many radionuclides behave similarly to certain non-nuclear contaminants, knowledge of the behaviour of radioactive contaminants often helps to assess the transport and fate of the latter. The radioactive decay characteristics of certain natural radionuclides (e.g. ^{210}Pb) make them excellent geochronological tools for dating the sequence of sediment layering in certain marine areas. This helps to establish the history of pollutants in the sediments. Similarly, accretion rates of ecologically important marshlands can be established by examining residual radionuclides in individual strata from cores of marsh muds. Radioisotopes of analogue heavy metals, particularly gamma emitters, have also proved useful for studying heavy metal contaminants in water, sediments and organisms.

In connection with the ever-greater number of harmful algal blooms being experienced in coastal waters, the recent use of tritiated saxitoxin for the production of marine algal toxin standards has helped Member States develop and employ rapid assay techniques for measuring toxicity in marine foods suspected of harbouring these algal toxins.

Submarine groundwater discharge (SGD) is an important pathway for the transport of contaminants to the sea and a principal component of fresh water supply to the coastal zone. It can also cause substantial loss of fresh water from arid regions and be responsible for limiting salt water intrusion into aquifers. Applications of stable and radioactive isotopic tracers include continuous monitoring of ^{222}Rn in coastal waters to get information on changes in SGD fluxes with time, and water and sediment sampling for laboratory analyses of radium isotopes, ^3H , ^{14}C and stable isotopes of water, helium, carbon, nitrogen and strontium. The main contamination studies include analyses of heavy metals, nutrients, oil and sewage contaminants. Analyses of a range of isotopic tracers and contaminants at the aquifer-marine interface permit integrated flux estimates of SGD in coastal zones not possible by other methods.

Marine antifoulants are the biocides added to marine paint to prevent the growth and accumulation of organisms on ship hulls and maritime structures. They are toxic and are used on vessels of all sizes thereby ensuring worldwide dispersion. Whereas non-nuclear techniques provide the most viable means for determining biocide distributions in the marine environment, radiotracer and stable isotope techniques can provide complementary experimental data on the environmental behaviour and biological uptake of antifoulants.

Although sometimes considered expensive, nuclear analytical techniques can compete with non-nuclear methods in specific applications, certainly in cases where the basic operation of a costly infrastructure is secured or shared through national programmes. With higher demand for accurate environmental assessments the role of nuclear techniques is likely to be strengthened.

IV-1.2. Terrestrial Environment

Nuclear analytical techniques that have been used and proved to be most useful for assessing and controlling non-radioactive pollutants include neutron activation analysis; particle-induced X-ray emission; X-ray fluorescence; mass spectrometry; isotope dilution and related analyses, and stable isotope and radiotracer studies. Examples include the study of mercury pollution, where transformations between organic and inorganic forms are studied

using a variety of its isotopes; radiochemical neutron activation analysis of trace elements at extremely low levels, such as vanadium in biological materials. In particular these techniques are frequently used to study the health effects of airborne particulate matter in the range of 2.5-10 micron particle size.

The use of and large scale atmospheric tests of nuclear weapons (1945-1980) has been so far the largest source of anthropogenic radionuclides in the environment. Testing resulted in the global distribution of ^{90}Sr (600 PBq), ^{131}I (650 000 PBq), ^{137}Cs (910 PBq) and many other radionuclides including plutonium. In addition radionuclides have been released on a small and large scale after accidents such as the Chernobyl accident.

Radioactive residues also remain directly at the various test sites and close surroundings, and radioactivity has been released during the production of weapons material and weapons fabrication. The resulting radiation doses to humans are mainly due to ingestion through contaminated food (^3H , ^{14}C , ^{90}Sr , ^{137}Cs) and external irradiation from ground deposition (^{95}Zr , ^{106}Ru , ^{137}Cs , ^{144}Ce).

Also, energy production by fossil fuels and nuclear power plants as well as industrial and mining activities often release, intentionally and unintentionally, radionuclides and other polluting elements and compounds into the environment, often leading to public concern about the risks involved.

The fallout radionuclides have been used as tracers for understanding and investigating atmospheric and environmental processes, but not all countries have laboratories equipped to make the requisite measurements. Understanding the fate of terrestrial pollutants for protective measures requires a proper assessment of the radiological and conventional risks, which requires the ability to perform accurate, representative sample measurements to internationally agreed and harmonised procedures, particularly in cases of transboundary transport of released pollutants, both radioactive and non-radioactive. International projects are being implemented to make available a structured network of laboratories for accurate analyses of environmental samples from accidental releases of radioactivity, and also to assist in the assessment of radionuclide concentrations at specific contaminated sites.

Proper models and integrated approaches to predict the environmental fate and the impact on human health of contaminants have to be developed and/or adapted to specific circumstances, including quantification of transfer to foodstuffs different from Western European consumption habits. The driving parameters must be determined, as well as ways in which they can be influenced to allow more effective and site specific remediation strategies and management after radionuclide releases. This will contribute to the production of safe food that does not exceed internationally agreed intervention limits for consumption and trade.

IV-2. DEMINING

There are approximately 60 million abandoned landmines in more than 70 countries. The number of new landmine victims is estimated at 15 000 to 20 000 per year.

Humanitarian demining requires the complete removal of all mines so that the cleared area can be returned to normal use. It is estimated that demining by manual means can clear only 10 m² per day per deminer and that one deminer is killed for every 2 000 mines cleared.

One of the major challenges in humanitarian demining is to discriminate between harmless objects and landmines. Increasing the sensitivity of metal detectors makes them sensitive to small pieces of scrap metal often found in mine-affected areas. A number of advanced mine detection techniques, such as, ground-penetrating radar, infrared thermography and advanced metal detectors, are emerging as complements to current manual methods. Each of these techniques only detects “anomalies” in the ground, and is unable to determine if an explosive agent is present or not. Irradiation of an identified anomaly with highly penetrating neutrons offers the potential for explosive identification through detection of secondary radiation and/or backscattering of the interrogating neutrons.

One of the most promising techniques is the pulsed fast-thermal neutron analysis (PFTNA), which uses a small neutron generator from which neutrons are emitted in bursts lasting for a few microseconds. Even though the principle is now well established, the focus of research is on enhancing the sensitivity for detecting small quantities of explosive, typical of an anti-personal landmine, at a reasonably good speed. Several devices based on PFTNA and neutron backscattering are being developed and will be tested under field conditions in the near future, for which the IAEA is implementing a Technical Co-operation project in Europe.

IV-3. IMPROVING INDUSTRIAL PROCESSES

Many industries use radioisotopes and/or radiation in their manufacturing processes and for improving the quality of their products. Radioisotopes can alleviate the need for dismantling equipment and often allow testing to be carried out during operation. Most such applications are non-destructive, non-invasive and often without competing alternatives.

The main industrial applications of radioisotopes and radiation may be classified as:

- Tracer applications to obtain information on flow and residence time in a process vessel, mixing, etc.
- Sealed source applications, in which sources are used for level gauging, control of thickness, moisture and density, nondestructive testing, blockage location in underground pipelines and column scanning. These measurements can lead to substantial improvement of the process and rectification of any defects.
- Radiation processing, which is one of the largest industrial applications. Ion beam and electron accelerators as well as ⁶⁰Co irradiators are important in this area.

Short-lived radioactive tracers are widely used in petrochemical, chemical and mineral processing industries for examining malfunctioning reactor vessels and optimizing process parameters. The benefit-to-cost ratio is high. For example, a major oil company increased production from 70 000 barrels per day (design capacity of 80 000 barrels) to 100 000 barrels per day. Radiotracer studies revealed that the mean residence time of water and oil in the separator column was one quarter of the design value. Modifications led to a daily increase of \$600 000 in production value. Radiotracers are also often used for the detection of leaks

in long underground petroleum, gas, and oil transport pipelines, and for such diverse tasks as aiding in desilting studies for harbours.

Sealed sources (^{60}Co , ^{192}Ir etc.) are used extensively in nondestructive testing of fabricated components to detect cracks and other flaws. Radiographic testing is essential for all fabricated equipment, pipelines and reaction vessels in modern industries, such as the automotive, shipping, air, power and petrochemical industries. Sealed sources are also employed to examine blockages in pipes and malfunctioning reactors in industry with benefits comparable to those with tracers.

Data from Japanese industries (as an example from a developed country) illustrate the major uses of radiation processing. There are three main components: polymer processing, sterilization and food irradiation. The industrial sectors employing polymer processing are shown in Fig. IV-1, together with the dollar value of those industries to further illustrate the industrial scale of operations. Processing is carried out mainly by electron beams from accelerators.

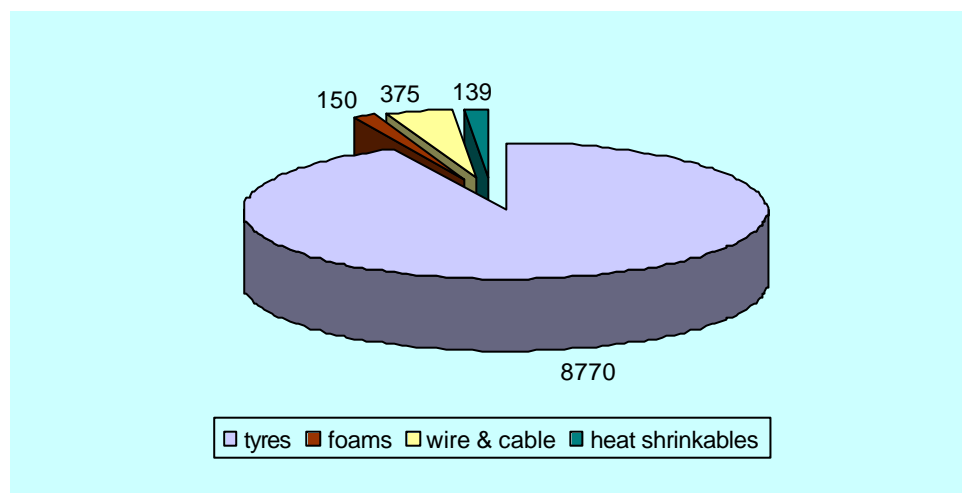


Figure IV-1. Main industrial products from polymer processing in Japan (millions of dollars)

Other industrial applications include radiation sterilization of disposable medical/sanitary products such as gloves, syringes, contact lenses and sutures. A number of techniques are used, and their relative shares are shown in Fig. IV-2. Gamma irradiators, based on ^{60}Co , are the mainstay. Gamma cell irradiators are also used for irradiation of blood to be used for transfusion, particularly for weakened patients or in bone marrow transplants. Gamma irradiators are also used for tissue graft sterilization. This process is becoming increasingly important as commercial and public sector tissue banks have recognized the freedom of the resulting tissue from contaminants which arise from gas and chemical sterilisation.

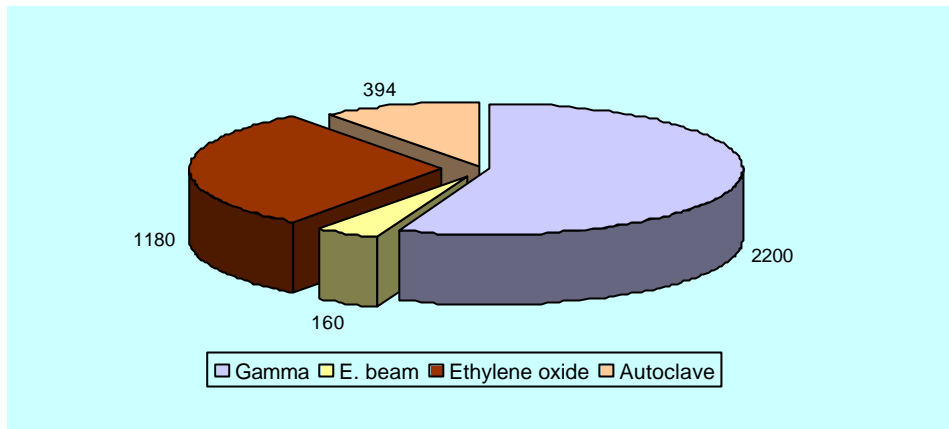


Figure IV-2. Share of different sterilization methods in Japan (millions of dollars)

As for future trends, radioisotopes and radiation industrial applications are not likely to be replaced by other processes in the foreseeable future. On the radiography scene, sealed radioisotope portable/transportable X-ray machines or accelerators are replacing radiation sources. Radiation processing in the semiconductor and polymer industries is an area of growth, and emerging areas include radiation-processed natural polymers.

Another promising area is the use of radiation in effluent treatment. Currently three coal-fired power plants (approximately 100 MW(e) capacity) in China, Japan and Poland have electron-beam-based components to remove sulphur and nitrogen oxides from the effluent gas and to generate, as a by-product, ammonium nitrate fertilizer. In Korea, the possibility of radiation-assisted effluent treatment of wastewater from a dye chemical complex is being investigated on a pilot scale, and a demonstration plant is now planned. This successful experience should have a beneficial impact on other industries producing wastewater containing organic pollutants.

REFERENCES

- [1] INTERNATIONAL ATOMIC ENERGY AGENCY Web Site: <http://www-nds.iaea.org>.
- [2] NUCLEAR ENERGY INSTITUTE, Medical and Industrial Uses of Radioactive Materials, Fact Sheet, Washington, D.C. (www.nei.org), July 2000.
- [3] MAKKUCHI, K., Radiation Processing in Japan. Extracts from a report of a study group organised by the Japan Atomic Energy Research Institute, Tokyo (1999).
- [4] INTERNATIONAL ATOMIC ENERGY AGENCY, Research Reactor Database, (<http://www.iaea.org/worldatom/rrdb>).
- [5] AMALDI, U., The Importance of Particle Accelerators, Europhysics News 31 (6), (2000).
- [6] INTERNATIONAL ATOMIC ENERGY AGENCY, Report of the Expert Panel on “Evaluation of IAEA Fusion Activities” (2001).
- [7] INTERNATIONAL ATOMIC ENERGY AGENCY, Summary of ITER Final Design Report, ITER EDA Documentation Series No. 22, Vienna (2001).
- [8] INTERNATIONAL ATOMIC ENERGY AGENCY, Power Reactors Information System (PRIS) Database, (<http://www.iaea.org/programmes/a2/>).
- [9] INTERNATIONAL ATOMIC ENERGY AGENCY, *Reference Data Series No. 1*, Vienna, July 2000 and July 2001.
- [10] EUROPEAN COMMISSION, ExternE 1998, Externalities of Energy: New Results, Directorate General XII, Science Research and Development, L-2920 Luxembourg.
- [11] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE: Climate Change 2001: Mitigation. Third Assessment Report of the United Nations Intergovernmental Panel on Climate Change, Chapter 3, Cambridge University Press, Cambridge, UK (August 2001).
- [12] RIAHI, K., and ROEHRL, R.A., Energy Technology Strategies for Carbon Dioxide Mitigation and Sustainable Development, Environmental Economics and Policy Studies, Vol. 3, No. 2, pp. 89-124.
- [13] ORGANISATION FOR ECONOMIC COOPERATION AND DEVELOPMENT: Projected Costs of Generating Electricity: Update 1998. OECD, International Energy Agency (IEA) and Nuclear Energy Agency (NEA), Paris, France.
- [14] Clinica’s Complete Guide to Diagnostics Volume 1: Successful Business Strategies for Companies in the Diagnostics Industry, CBS798E, PJB Publications Ltd., January 1999.

- [15] TESHIMA, T. et al., A Comparison of the Structure of Radiation Oncology in the United States and Japan, *Int J Rad Oncol Biol Phys* 34, (1996) 235-242.
- [16] PHILIP, J., Ending Malnutrition by 2020: An Agenda for Change in the Millennium. *Food and Nutrition Bulletin*, United Nations University, Tokyo, Vol. 21 (3), supplement (2000), 88 pp.