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NUCLEAR TECHNOLOGY REVIEW 2000

1. This document has been prepared in response to a proposal made by some Member States at the March 1999 meetings of the Board of Governors that the Secretariat prepare a *Nuclear Technology Review* similar to its *Nuclear Safety Review*.

2. The *Nuclear Technology Review 2000* focuses on the contribution of nuclear technologies for both power and non-power applications:

- Part I provides a global perspective on the prospects for nuclear power. It focuses on three key factors that will determine the role of nuclear power in meeting growing energy demands for energy and electricity: public acceptance; competitiveness; and energy sustainability.

- Part II describes the current status of non-power applications of nuclear and related techniques and covers significant developments in recent years. It also looks ahead to future trends in the diverse applications of these techniques.

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.

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.

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INTRODUCTION

Nuclear power is an important contributor to the world's electricity needs. In 1999 it supplied more than one sixth of global electricity and a substantial 31% of the electricity in Western Europe. Nevertheless, nuclear power is at a turning point, there being no consensus concerning its future role. A sizeable portion of public opinion remains hesitant or opposed to its use. With current trends, nuclear power's share of global electricity supply could decrease significantly in the decades ahead.

Several issues are central to the current situation with nuclear power. In a greatly liberalized and competitive electric power industry, return on investments can be the main consideration. In investment decisions, the high up-front capital costs for new plants, relatively long construction times and political uncertainty more than offset the nuclear fuel cost advantage. On the public and policy level, concerns linger over safety and high level waste disposal. For some, nuclear power heightens weapons proliferation concerns.

Nevertheless, a new and powerful issue has surfaced that could significantly influence the global energy situation. There is a general recognition that the huge increase in energy production anticipated for the 21st century could lead to damaging health and environmental impacts. It is bringing about some political awareness of nuclear power's potential role in the sustainable management of energy as it delivers large quantities of energy without releasing common atmospheric pollutants and greenhouse gases.

The review begins with *the global nuclear power picture* and follows with *addressing the issues*, which examines key topics that govern the growth of nuclear power: economic competitiveness, which in many situations is the determining issue, and the management of spent fuel and radioactive waste. There is a limited coverage of nuclear safety and non-proliferation, additional topics relevant to the growth of nuclear power, as other Agency documents consider these subjects in great detail. *Sustainable energy management* and the need to reduce global environmental emissions are treated separately. The review ends with *looking to the future*, a survey of upcoming events that could have a bearing on nuclear power prospects in the near term.

Generally, a national and regional approach has been used to bring out the many and differing considerations that influence energy decisions. Development patterns, economic factors, availability of energy resources and the historical position of nuclear energy differ markedly for industrialized countries, developing countries and those with economies in transition.

The *Nuclear Technology Review 2000* is submitted in response to a request by some members of the Board of Governors who suggested that the Agency also prepare a nuclear energy review similar to the *Nuclear Safety Review*.

1. THE GLOBAL NUCLEAR POWER PICTURE

This section surveys nuclear power worldwide and uses selected developments in 1999*[1] to illustrate the current situation. With the short term outlook not promising in many countries, it also brings out the need to gain public acceptance.

1.1. A NATIONAL AND REGIONAL SURVEY

Globally, in 1999 there were 433 operating nuclear power plants (see Appendix 1) providing roughly 349 GW(e), some 16.1% of global electricity, a share similar to that seen over the past decade. As a capital intensive and advanced technology, about 83% of nuclear capacity is concentrated in the industrialized countries. The largest regional percentage of electricity generated through nuclear power is the 43% in Western Europe where the shares in 1999 in France, Belgium and Sweden were 75%, 58% and 47%, respectively (Fig. 1). These are also the highest country values globally except for the 73% share in Lithuania that is supplied by two large RBMK units of Soviet design.

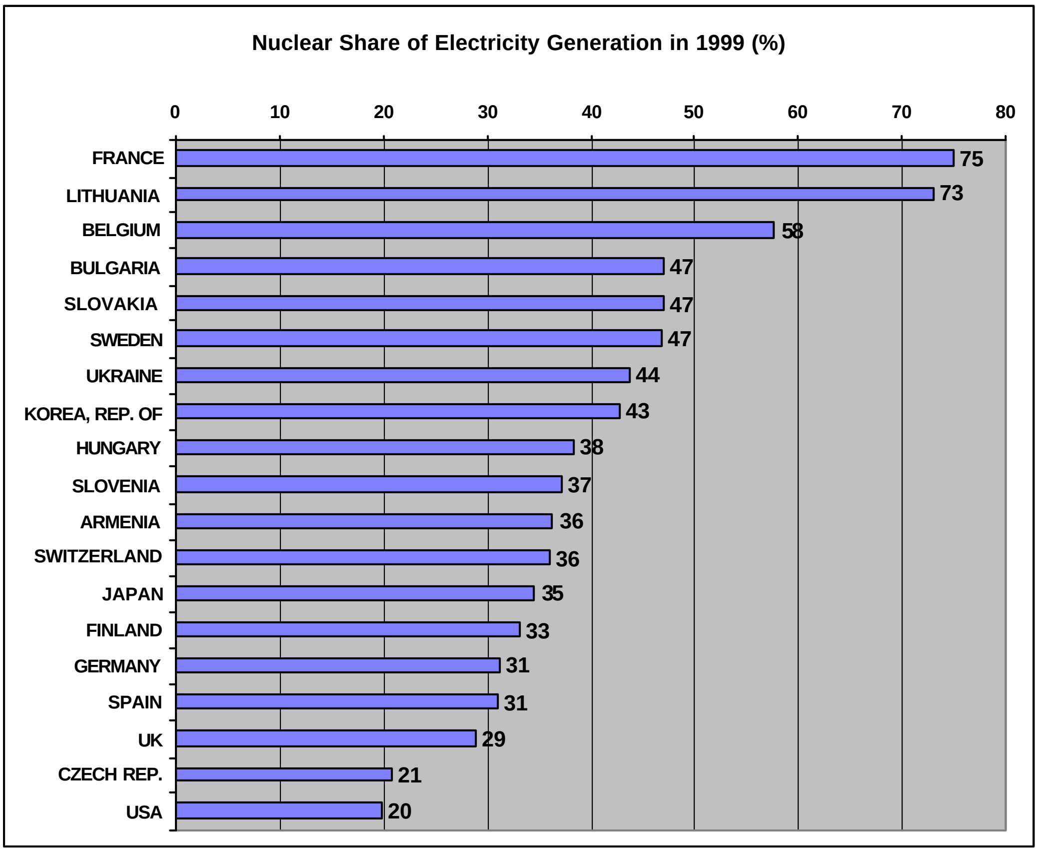


Fig. 1. Nuclear share of electricity in 1999 [IAEA]

[1] *The document has been updated for events in 2000 following the recommendations of the March and June meeting of the Board of Governors.

1.1.1. North America and Western Europe

In North America, where 118 reactors supply 19.8% of electricity in the USA and 12% in Canada, there have been no new orders during the past two decades and the number of operating reactors is in a slight decline. Although existing plants can be competitive due to past depreciation of investments and low fuel costs, there appears to be no market for the new large and capital intensive plants that the industry now offers.

In Western Europe, with a total of 150 reactors, the most likely short term picture is nuclear capacity remaining at about its present level in the coming years. There will be some unit capacity upgrades and life extensions of existing plants. Although Belgium, Germany, Spain, Sweden and Switzerland rely substantially on nuclear power, they do not currently intend to construct new plants. Belgium, Germany, the Netherlands and Sweden are planning gradual phase outs. In Austria, Denmark, Greece, Ireland, Italy and Norway, restrictions prevent the use of nuclear power.

A number of developments in 1999 illustrate the current situation:

- Neither in North America nor in Western Europe were any reactors under construction after the connection of Civaux-2 to the French grid towards the end of the year.

- In Sweden, the Barsebaeck-1 unit was shut down in November as required by a 1997 Government action. This has been considered as a first step in a long-term energy policy, aiming at increasing the share of renewable energy sources in combination with energy conservation. Recent opinion polls show 80% of the public wanting continued operation of the remaining 11 reactors.

- In Germany, there exists a basic political consensus in the governing coalition about the phase out of nuclear power. The possible means and timing of implementing the decision for the phase out have been negotiated and a principal agreement was reached in May 2000.

- In Finland, a new political coalition has kept open the option for a fifth reactor. The country's two utilities have submitted environmental feasibility studies.

- In the USA, the Westinghouse advanced mid-sized AP600 reactor design, which incorporates *passive* safety features and a 60 year plant lifetime, received regulatory certification.

1.1.2. Eastern Europe and the Newly Independent States (NIS)

In Eastern Europe and the NIS where there are 68 reactors, the debate continues in some countries over the need to finish construction of partially built plants. A few will be completed, while ageing units are shut down, some prematurely. The majority of plants have already operated for more than half their original design lifetime. Economic conditions and financing possibilities along with security of supply considerations will determine the future course. Relevant 1999 developments include the following:

- The European Union continued to seek closure of first generation Soviet designed water cooled WWER and graphite moderated RBMK reactors. Bulgaria committed itself to close down Kozloduy units 1 and 2 before 2003. Slovakia announced the closure of Bohunice units 1 and 2, one in 2006 and another in 2008. Lithuania agreed to an early closure of one of its two RBMK reactors at Ignalina in 2005.

- In 1999, the Czech Government decided to complete the construction of two substantially modernized WWER-1000 units at the Temelin nuclear station, with the first unit due to start in the fall of 2000 and the second one to follow in 18 months. In January 2000, an approved Energy Policy maintains open the nuclear option including the possibility of additional units after 2015.

- In Slovakia, a modernized WWER-440 unit at Mochovce-1 began operation in early 1999, as did the similar Mochovce-2 unit towards year end.

- Kazakhstan shut down its only power reactor at mid-year. The 70 MW(e) fast breeder reactor BN-350 had operated for more than 25 years, supplying electricity as well as heat for seawater desalination.

- In the Russian Federation, the completion of three new units: a WWER 1000 at Rostov and one at Kalinin, plus an advanced RBMK at Kursk has been initiated. In 1999, the Rosenergoatom consortium and St. Petersburg plant produced 13% of the country's electricity.

- Ukraine, towards year-end, restarted Chernobyl Unit 3, the only remaining reactor at the site, after failing to obtain satisfactory agreements from other countries for the completion of replacement units.

1.1.3. Far East, South Asia and the Middle East

In the Far East and South Asia, where there are 90 reactors, planning for an expansion of nuclear power continues, particularly in China, India, Japan and the Republic of Korea. This is likely to be the only region where the use of nuclear power will grow over the short term. However, the financial crisis during the past several years has slowed down the large regional increase in energy demand that was foreseen in earlier years. Relevant 1999 developments follow:

- In north eastern China, construction of a WWER-1000 unit began at Lian Yungang (Tianwan 1) with a second construction start expected this year. Construction of two French PWR units at Lingao proceeded on schedule. At Qinshan, construction continued on two domestically designed PWR units and two Canadian heavy water units.

- In Taiwan, China, construction of its 7^{th} and 8^{th} units at Lungmei continued, both being advanced boiling water reactors. Startup is expected in 2004 and 2005.

- India completed construction of two indigenously designed heavy water units, one at Kaiga that is already connected to the grid and another at Rajasthan which achieved criticality towards year end. An additional unit at each site should be finished this year.

- India was also set to receive two WWER 1000 MW(e) units as the Russian Federation continued to actively market its large PWR plant.

- In the Islamic Republic of Iran, the Russian Federation increased its co-operation to complete unit 1 at Bushehr with a WWER-1000 unit. The nuclear supplier was originally Siemens Kraftwerk Union.

- In Japan, construction began at two sites for 1350 MW(e) advanced boiling water reactors.

- In the Republic of Korea, the Wolsong-4 heavy water CANDU reactor began commercial operation, bringing the total of operating plants to 16. Construction began on two indigenous standardized design units.

- Pakistan saw the completion of its second nuclear plant, a Chinese designed 300 MW(e) unit. Connection to the grid is expected during the first quarter of this year.

- The Korea Peninsula Energy Development Organization and the Korea Electric Power Corporation signed a long-awaited turnkey contract for building two 1000 MW(e) plants in the Democratic People's Republic of Korea. Completion of the first unit could be in 2007 with the second unit following a year later.

1.1.4. Latin America and Africa

Latin America and Africa currently account for less than 2% of global nuclear capacity. Completion of two units and a growing interest in small units can be seen in several 1999 developments:

- In Brazil, the German designed 1300 MW(e) Angra-2 plant was completed and connection to the grid is expected in 2000.

- Egypt continued negotiations with German, Canadian and US companies to build small nuclear stations for generating electricity and seawater desalination.

- South Africa continued design efforts on a 110 MW(e) gas cooled Pebble Bed Modular Reactor (PBMR). In April 2000, the South African Cabinet gave formal approval to Eskom to continue with a detailed feasibility study of the PBMR and to proceed with an environmental impact statement, including public consultation.

- In Argentina, the National Congress passed a law in November 1999 enabling funding of the prototype of the intrinsically safe and locally designed CAREM low-power reactor (25 MW(e)). Also, at the beginning of 2000, the Government established an interministerial committee with a mandate to formulate without delay a recommendation regarding finalization of the construction of the 745 MW(e) PHWR Atucha II nuclear power plant.

1.2. THE NEED FOR PUBLIC ACCEPTANCE

Although nuclear power is clearly an important contributor to regional as well as national electricity supply worldwide, with a share of 25% or more in 17 countries, there is no universal consensus on its future. The tenuous position of nuclear power is seen by projections indicating that the global nuclear share of electricity supply will not keep pace with electricity demand growth.

The OECD International Energy Agency (OECD/IEA) projects a fall from a 17% global share to roughly 10% over the next two decades with the total nuclear installed capacity remaining roughly at today's level. A more pessimistic picture is evident in a 10% installed capacity decrease for the same time period projected in the US Energy Information Administration (EIA/DOE 1999) mid-range reference case. A low energy growth case projects a fall of as much as 50% with only the high growth scenario showing an increase, this by some 25%. For the industrialized countries, their capacity does not grow even for the high growth scenario and there is a significant 25% decrease for the reference case, more than double the global decrease of 10%.

There is no simple answer to explain the decline in the fortunes of nuclear power from the enthusiasm of the 1960s and early 1970s to its low today. In different countries the change from a generally positive to a generally negative attitude occurred at differing times and to differing extents, with differing reasons as the main driving forces. There are a number of countries where attitudes have not changed much. In these, political support for nuclear energy is seen as an important sign of support for local technology and of the importance of decreasing dependence on others for energy supply.

1.2.1. Safety concerns

Unquestionably the accidents at Three Mile Island and Chernobyl severely influenced attitudes towards safety and damaged trust in an industry that had maintained that severe accidents were improbable or even impossible. Nevertheless, numerous lessons came out of these two events. Most important was the conclusion that a better understanding of the human role in plant operation was needed. The industry responded through technological safety improvements, such as updated control room layouts providing operators with clear and necessary information and improved training and operational procedures along with exacting internal and external audits of operating and safety performance.

The rapid gains seen over the past two decades — clearly shown by the Agency and the World Association of Nuclear Operators (WANO) safety and performance indicators outlined later — that are common to maturing industries will naturally level off. Nevertheless, safety through human and technological improvements will need continuing priority, with sharing of industry experience an essential component. Today, the Agency has a wide range of programmes and technical groups covering reactor engineering and technology that can promote the necessary information exchange. But, for the public, the reliable and safe performance of existing plants worldwide over many years will be the clearest demonstration of nuclear safety.

1.2.2. Waste concerns

The lack of adequate information is a factor that allows the radioactive waste issue to remain a public concern. A recent large opinion survey carried out by the EU of some 1000 people in each Member State showed that only 20% considered themselves well informed about radioactive waste, 44% considered themselves to be poorly informed and 32% very poorly informed. Some 50% thought nuclear waste was disposed of at sea or sent to other countries.

The disposal of high level radioactive waste continues to be a major public acceptance issue today. Although the scientific community is generally convinced that disposal is technically achievable, the reality that waste is accumulating and disposal has not yet taken place leads to the perception that it can not be done.

1.2.3. Risk and benefits

Public attitude research also suggests that a major factor in moving people to an anti-nuclear position is the increasing belief that nuclear power offers few, if any benefits. Nuclear plants are seen only as sources of electricity, and the public has been convinced that sufficient alternatives exist. In addition to traditional coal, there is increasingly gas and a variety of renewables. The opinion that nuclear power is also too expensive has been strengthened by electric utilities turning away from nuclear for new plant investments. There are many who believe that nuclear power must be seen as having clear economic and environmental benefits before public confidence can be restored. Against the background of recent developments worldwide, Sections 2 and 3 of the Review address the competitiveness, waste and environmental topics.

2. ADDRESSING THE CENTRAL ISSUES

This section describes the changing electricity market and the current competitive disadvantage of capital intensive nuclear plants as well as the distinct advantages of existing ones. The potential impact of *externality* costs for environmental and health effects is brought out. A new generation of plants is one way to address competitiveness, and a diverse set of advanced designs is reviewed. They span *evolutionary* to *innovative* systems, which, in addition to competitiveness, address safety, waste and proliferation concerns. The section concludes with the current spent fuel and radioactive waste situation, and a review of progress in demonstrating high level waste disposal.

2.1. ECONOMIC COMPETITIVENESS

The rapid growth of nuclear power occurred during a period when the electricity industry worldwide was commonly operated under varying degrees of government control. Electricity was considered an essential service and prices were generally the cost of production plus a profit set by a governmental body. Additionally, subsidies could be used to favour one fuel over another for social or energy security reasons.

During the past decade dramatic changes have taken place in many countries. Electricity supply is no longer a monopoly in the possession of the government or a few suppliers. It is also in some cases no longer a single industry. Generation, transmission (over long distances), distribution (over short distances) and marketing (to final consumers) can be separate entities. Particularly generation and marketing are taking place in highly competitive environments where short term pricing contracts are common, driven in part by the availability of low cost gas generating plants for peak and baseload supply. A number of developments in 1999 illustrate the move towards market liberalization:

- In Canada, there was a major restructuring of the Ontario Hydro utility that operates all but two of the country's nuclear units.

- In Germany, the second and third largest power producers, VEBA and VIAG, announced merger plans and the biggest power utility, RWE, was in the market for a merger.

- In the USA, the trend continued toward operation of existing nuclear plants through management companies, such as AmerGen, Entergy, FirstEnergy, Nuclear Management Company and Southwest Alliance. A plant outside of Boston became the first nuclear unit sold outright by an operating utility, and in late 1999 three other sales were announced.

- Also in the USA, Northeast Utilities and ConEd merged at year-end to become the largest electricity distribution utility.

- In Western Europe towards year-end, Framatome and Siemens announced a joint entity for their nuclear activities. It followed a consolidation of Westinghouse Electric with British Nuclear Fuels PLC, the latter having recently also purchased ABB nuclear power operations.

- In Eastern Europe and the CIS, electricity market liberalization was becoming widespread, although the nuclear sector remained under government direction.

Worldwide, utilities increased the competitiveness of their existing plants through capacity upgrading and license renewals that permit plant life extensions. In the USA, 26 of the 101 operating plants have signalled their intent to extend operation for an additional 20 years.

2.1.1. Comparative costs of new plants

Joint studies by the IEA and the OECD Nuclear Energy Agency (OECD/NEA) have shown that new nuclear plants in OECD countries can be competitive with other baseload electricity generation alternatives only under certain conditions that can vary considerably nationally, such as financing, construction periods, regulatory considerations, and the cost and availability of alternative fuels.

A 1998 study update showed that for a rate of return on the order of 5% annually on long term investments (linked to the so called discount rate), nuclear could be a low price alternative to fossil fuels in some countries as low fuel costs offset high initial capital requirements. For the higher rates of return and short pay-back periods that are commonly expected today, it is difficult for nuclear to compete at all with gas, particularly combined cycle, or even with coal. Along with nuclear, large hydroelectric projects and capital intensive renewables, such as solar, could also be adversely affected by the need for high rates of return.

The IEA/NEA study shows that capital requirements for nuclear construction are the greater part of generation costs, typically 60%, with operation and maintenance at 25% and fuel the remaining 15%. Capital for fossil plant construction can be significantly lower, with fuel the major portion of generation costs, at some 45% for coal and some 70% for natural gas. The result is that the generating cost per kW(e) for a gas combined cycle plant is generally lower than for other fossil fuel systems and can be substantially below nuclear power. Today, a gas plant can be built at one-fourth the cost of an equivalent nuclear plant and in less than one-third the time. The following list of construction costs, time periods and generating costs presents ranges indicative of current conditions, with country specifics causing the differences:

Cost per kilowatt	**Time to startup**	
	$	**(years)**
Nuclear, LWR	2000 – 2500	6–7
Nuclear, best practice	1500 – 2000	4–6
Coal, pulverized	1000 – 2000	4–5
Gas, combined cycle	500 – 900	2–3

Range of projected generation costs calculated with national assumptions (US Mills per kWh) [OECD]

	Minimum	**Maximum**	**Median**
Coal	24.7	78.5	49.7
Gas	23.7	100.1	48.5
Nuclear	22.3	78.4	47.5
Others	30.0	119.1	69.1

The capital intensive nature of today's nuclear plants has contributed to bringing new construction to a minimum, as is evident by only a handful of new construction starts over the past few years. But, direct plant construction costs are not always the determining factor. Although a gas plant could appear to be a low cost option, if it is not near a gas pipeline, building delivery systems could significantly change the picture. The infrastructure requirements for coal, such as transport, handling and storage, can also have a determining influence on the energy choice.

In addition to investment returns, limiting investment risks is an issue. Investors are keenly aware that nuclear facilities have been at risk for both completion and operation. The risks of prolonged delay are seen in the USA, Brazil and a number of developing countries where delays have exceeded 10 years. Also a reality are several finished plants never placed in operation, such as in Austria, Philippines and the USA. And, investors have been made acutely aware that in a matter of minutes, a multibillion dollar nuclear asset can become a liability through a severe accident. The financial risks of regulation have also been much greater for nuclear than for other forms of power generation, although signs of change are becoming clear not only in the USA through recent use of the Clean Air Act, but also elsewhere.

On the positive side, nuclear power can offer significantly lower fuel supply and price instability risks as the required fuel quantity is small and strategic inventories for many years can be readily set up. Clearly, where indigenous fossil fuel resources are lacking, nuclear power can contribute substantially to security of supply and price stability as it does today in Finland, France, Sweden, the Republic of Korea and Japan.

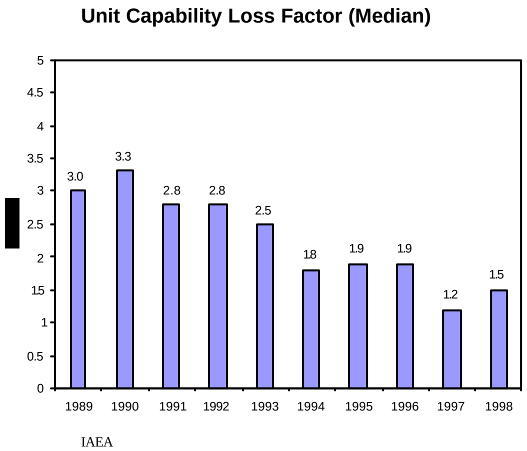
The newly released *WEC Statement 2000* by the World Energy Council also notes that while the short-term impact of regulatory reforms in most countries is to make new nuclear plants less attractive options, this is not the case in developing countries where additional capacity is needed, nor will it be so in industrialized countries 10 years from now. For that reason WEC stresses the importance of keeping the nuclear option open, with R&D devoted to both evolutionary technologies and new small size designs for markets with less concentrated electricity demand.

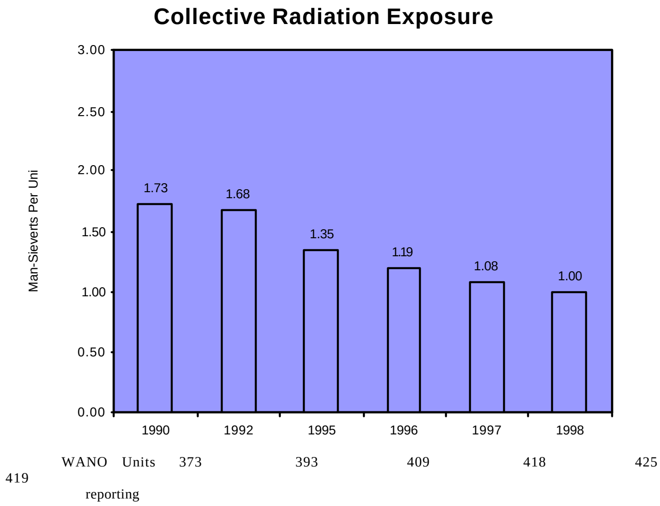
2.1.2. Reducing today's construction and operating costs

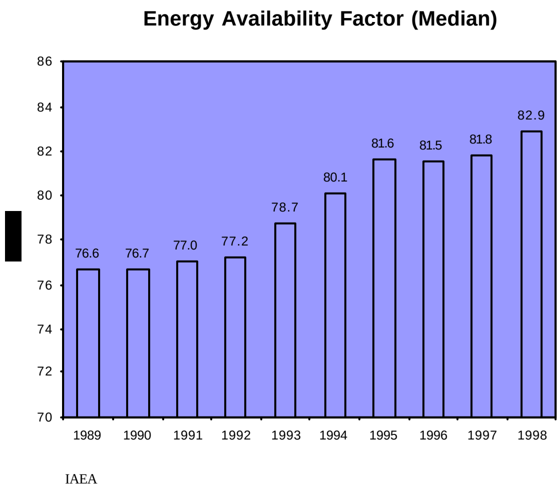
Competing with fossil and especially small gas units where an investment can often be recovered before a nuclear plant is even operational, requires substantially improved economics that can be brought about by lower initial investment and operating costs. Recent standardized plants with multiple units at the same site have seen construction periods shorten considerably and operating costs reduced. The French REP 2000 series is estimated to have led to savings of 20 per cent in capital costs and other economic benefits, such as reduced expenses for staff training and spare parts storage. Nuclear units commissioned recently in Japan and the Republic of Korea were built in 4 to 5 years with reduced capital costs and with design lifetimes of some 50 to 60 years, in effect decreasing operating expenses.

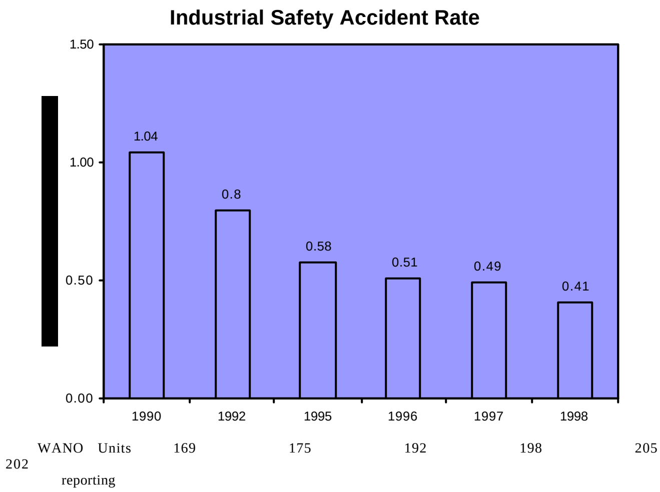
Competitive disadvantages influencing decisions to build new nuclear plants in countries with liberalized energy markets do not extend to existing ones, particularly when capital investments may have been depreciated or written-off during ownership transfer. Today, with the exception perhaps of hydroelectric, well managed nuclear plants, with their low fuel costs and steadily declining operation and maintenance costs, are often among the least expensive base load power to operate. In Germany average generation costs at largely depreciated existing nuclear plants are currently some 30% lower than for new gas baseload plants. This advantage has been sufficient to encourage owners of existing plants in numerous countries to invest in life extension programmes and to increase total plant generation capacity along with on-line time.

A number of factors account for the improved performance. Competitive pressures and the ongoing utility restructuring that includes consolidated and modernized management approaches are some. The steady performance gains worldwide over the past decade are seen in various indicators released annually by the Agency and by WANO that show steady increases in capacity factors and decreases in unplanned reactor shutdowns, which now occur roughly once per year compared to some 7 per year two decades ago (Fig. 2). Plants with good performance are generally not only more reliable, but also have high margins of safety as seen by the consistent decrease in collective radiation exposures of workers and the industrial safety accident rate.









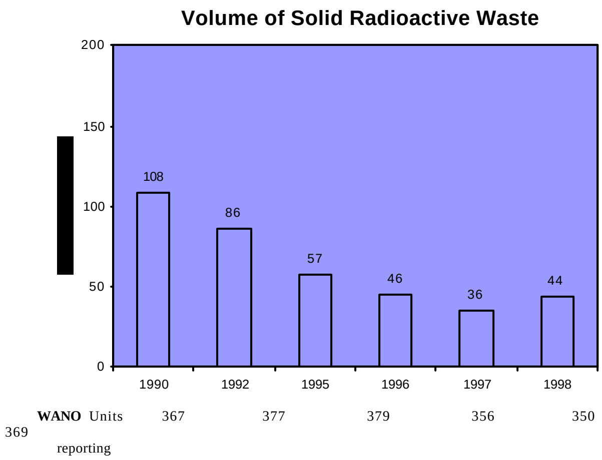


Fig. 2. Plant Performance Indicators (1998)

2.1.3. Externality costs

There are other costs that could change the competitive positions of the various energy sources. These include a range of so called *externalities* that are not generally factored into the market price of energy. Costs assigned to health and environmental effects through stringent requirements on releases and various ecological surcharges are already used in the industrial and transport sectors. They conform with the polluter pays approach.

Fossil fuels would bear the brunt of a cost placed on health and environmental impacts due to releases of noxious gases, toxic pollutants and particularly greenhouse gas emissions (GHG). Generally, renewables along with nuclear would be little effected. A 1998 IEA paper on *Climate Change and Nuclear Power's Future* illustrates the effects of a monetary cost or *carbon value* on GHG production, that would be applied to fossil fuels.

The addition of a carbon value of $30 per tonne to today's roughly $40-$60 coal price would increase the comparative cost of coal electricity by 10%-20% (Fig. 3). A currently implausible carbon value of $200 per tonne would increase the cost of gas electricity by some 40%. Clearly, carbon values would not change the generating costs of nuclear, hydroelectric and most renewable systems at all.

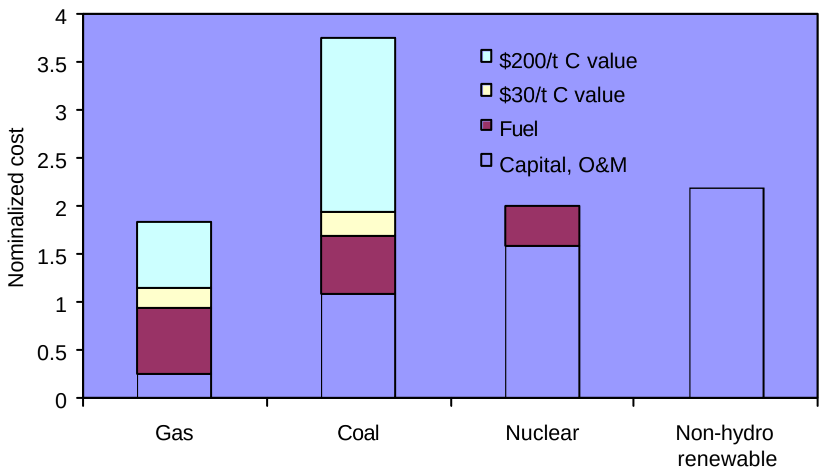


Fig. 3. Effect of carbon value on generation costs [IAEA]

Determining the cost impact of health externalities is not simple and is for that reason generally avoided. It requires consideration of occupational as well as public effects for the entire fuel chain — from fuel recovery to decommissioning — not only on a local scale, but also regionally. A comprehensive *ExternE* project of the European Commission (EC) developed full chain methodologies to place a monetary value on health impacts so the varying effects on generation costs could be seen.

The coal and oil plants considered, due to their large emissions and huge fuel and transport requirements, had the highest external costs as well as equivalent lives lost (based on loss of life expectancy). The costs for coal were some ten times higher than for nuclear plants and they would add significantly to generation costs, ranging from roughly 25% to more than a 100% increase. For some cases, equivalent lives lost approached 40 per 1000 MW(e) per year compared to less than one for nuclear and renewables.

A number of recent developments demonstrate that environmental considerations are increasingly impacting energy affairs:

- The UN Economic Commission for Europe continues to foster agreements on long-range transboundary air pollution, with the most recent on sulphur emissions, due principally to coal burning, entering into force in mid 1998.

- China also in 1998 strengthened its regulations for sulphur emissions.
- The US Clean Air Act governing acid gas (including sulphur emissions), along with ozone and particulate matter, is being more rigorously enforced in the energy sector. A late 1999 action calls for severely lower emissions from some Midwest plants seen as causing smog conditions in the Northeast. Cost implications could be some $1 billion.

- The International Organization for Standardization (ISO) is at an advanced stage of its evaluation of a *Life Cycle Impact Analysis* that uses consistent requirements in judging energy options for the influence of air emissions, waste and land use.

2.2. COMPETITIVENESS AND ENHANCED SAFETY THROUGH ADVANCED MODULAR DESIGNS

To meet the competitive challenge in the decades ahead, a new generation of advanced reactor systems is being developed. Current estimates exceed $2 billion annually for R&D by the nuclear industry and governments for both evolutionary and innovative designs. Evolutionary designs require moderate development efforts mainly through modifying proven features, while innovative designs call for substantial development efforts as well as pilot or demonstration plants. The evolutionary design efforts detailed below centre on improving today's generation of light and heavy water reactors. The innovative designs subsequently covered include these two reactor types and also gas cooled reactors; most are of small to mid-sized capacity below 700 MW(e). In a few countries there are continuing efforts to develop sodium cooled fast reactors aiming to increase the efficiency of uranium use in addition to economic competitiveness.

Some experts in the nuclear community advocate that nuclear energy should aim at a significantly more important role in the energy mix than it has today and is anticipated to have in the next 15-20 years. They consider that for large-scale nuclear energy development innovative reactor and fuel cycle concepts should be developed with significantly improved safety, waste and proliferation resistant features. New types of fast breeder reactors, accelerator driven systems (ADS) and other types of innovative reactor and fuel cycle systems for the long term are briefly described below.

In the safety area, modernized control rooms are only one of a wide range of improvements already employed or planned for advanced plants. Modern in-service inspection techniques through non-destructive surveillance of major reactor components and structures (pressure vessel, steam generators and containment) will be facilitated. Other advances are seen in upgraded instrumentation, new safety display software and modernized fire detection and suppression systems. Advanced features will also include improved fuel characteristics, passive safety systems (gravity and pressure differentials for safe shutdown) and severe accident mitigation features. The worldwide trends in advanced reactor designs are periodically summarized in status reports prepared by the Agency.

2.2.1. Evolutionary water cooled reactors

With almost 88% of global capacity in 1999 supplied by PWRs, WWERs and BWRs, evolutionary upgrades are under way in a number of countries. The drive is for increased competitiveness through reduced construction periods and improved operational performance along with enhanced safety features that include passive safety systems. Advanced HWR efforts are chiefly in Canada and India, with some focus on raising characteristically low and medium size capacities. The evolutionary designs covered should not call for demonstration plants. Early certification by governments would help avert the unpredictable delays that have driven up capital costs in the past.

LWR activities include the following:

- In China, a 600 MW(e) PWR design (AC-600) is based on the smaller Qinshan I unit and additionally has passive safety systems for emergency heat removal.

- France and Germany completed a basic design for a large 1545 MW(e) European Pressurized Water Reactor (EPR) in 1998. It meets European utility requirements and has lower operational costs along with substantially enhanced safety features. France already operates a number of standardized PWR units with advanced design features.

- In Germany, Siemens together with German utilities continued development of an advanced BWR design (SWR-1000) incorporating passive safety features.

- In Japan, advanced BWR units have been operating since 1996. A Technology Sophistication Programme is under way to develop a large 1500 MW(e) advanced PWR with horizontal steam generators.

- A Korean Next Generation Reactor based on PWR experience with the operating 1000 MW(e) Korean Standard Nuclear Plant has been under development since 1992.

- In the Russian Federation, efforts continued on three designs: an upgraded WWER-1000, a mid-sized PWR incorporating passive safety features and a design with system components inside the pressure vessel. The WWER-1000 is planned for units in China, India and the Islamic Republic of Iran and a regulatory licence has been issued for a future plant with two mid-sized units.

- Sweden and Finland continued work on advanced versions of BWR units operating in both countries that have improved performance and safety features.

- In the USA, large sized advanced PWR and BWR designs were certified in May 1997. Two of the advanced BWR units should be operational in Taiwan, China, during 2004. A mid-sized 600 MW(e) PWR that was certified in December 1999 has passive safety features, modular components for easier assembly and a 60 year plant lifetime.

HWR efforts include the following:

- In Canada, basic engineering continued on the CANDU-9 reactor. Two units of a smaller advanced CANDU-6 design are under construction in China.
- In India, construction of two 500 MW(e) units at Tarapur began in late 1998 that include feedback from the indigenously designed 220 MW(e) units.

2.2.2. Innovative gas, water and liquid metal cooled reactors

Evolutionary improvements alone may not revive the nuclear option globally. Innovative designs that turn from large to smaller units with greatly shorter construction periods and much lower capital costs may also be necessary. In addition to lower generating costs and enhanced safety they could include proliferation resistant features. Smaller units favour construction with factory built structures and components, including complete modular units for even faster on-site installation. Generally, the cost pattern would change from economy of size to economy of volume.

These smaller and likely easier to finance systems would be particularly effective in countries with modest electricity grids or areas without grid connections. They could also be used for district heating and desalination. The HTGRs being developed could additionally be used for co-generation of electricity and heat, and for high temperature heat applications. Prototype or demonstration plants would be needed for most of these innovative designs.

GCR activities include the following:

- In China, initial criticality of a small 10 MW(th) High Temperature Reactor for non-electric applications is planned for late 2000.

- In Japan, a small 30 MW(th) High Temperature Engineering Test Reactor (HTTR) began operation in 1998 for reactor development and for heat applications, such as hydrogen production through a high temperature steam and natural gas chemical process.

- The Russian Federation, USA, France and Japan have combined the efforts of MINATOM, General Atomics, Framatome and Fuji Electric for development of a 278 MW(th) Gas Turbine Modular Helium Reactor (GT-MHR).

- Nuclear power plant owners/operators and designers from South Africa, the UK, the USA and some other Member States are developing a 110 MW(e) Pebble Bed Modular Reactor (PBMR) with a once through fuel cycle and passive safety due in part to ceramic-coated fuel particles. The reactor concept was used in a German plant operated for 22 years. In 1999, a scale model criticality test was carried out in Moscow and an economic and technical feasibility review was completed through the Agency.

Work on LWRs includes the following:

- In Argentina, design work continues on a small 25 MW(e) reactor, CAREM, with integral steam generators that could be coupled to a desalination process in a cogeneration model.

- Japan is studying a small 50–300 MW(th) reactor for ship propulsion or local energy supply.

- In the Republic of Korea, a conceptual design of a 330 MW(th) System Integrated Modular Advanced Reactor (SMART) with integral steam generators for multipurpose application, including seawater desalination, is almost complete.

- The Russian Federation is considering a barge mounted version of a small sized reactor used in ice-breakers for electricity as well as heat generation in the northern part of Siberia. It could eventually be returned to the supplier for maintenance and/or refuelling.

HWR work:

In India, a vertical tube 235 MW(e) advanced reactor is under design that would use a thorium based fuel and incorporate passive cooling features.

Sodium cooled fast reactors:

A closed fuel cycle using plutonium from sodium cooled fast breeder reactors was originally chosen for a growing nuclear power industry. With the current stalemate there is interest in this technology in countries that consider nuclear power will have an important role in their future energy supply.

- In China, licensing efforts began in 1998 for a 25 MW(e) Chinese Experimental Fast Reactor. The project is currently in the detailed design stage.

- France, in 1999, began the first phase of decommissioning the Superphénix fast breeder. The lifetime of the smaller Phénix has been extended to further study mainly the transmutation of long-lived nuclear waste, and also plutonium-based fuels, and materials.

- In India, detailed design and technology development work for the 500 MW(e) Prototype Fast Breeder Reactor is being performed. A small fast breeder test reactor is currently operational.

- In Japan, the optimization design study of a 660 MW(e) Demonstration Fast Breeder Reactor was finalized. After a sodium leakage incident in 1995, the 280 MW(e) prototype MONJU was shut down. A thorough investigation of the accident's causes and a comprehensive safety review were carried out with design modifications proposed. The experimental fast reactor JOYO has been successfully operated as an irradiation test facility for fuels and materials. It is currently operated as a transition core towards the high performance irradiation MK-IV core.

- The Republic of Korea continued plans for a conceptual design of a 150 MW(e) plant to be completed by 2001 and a basic design to be completed in 2006.

- In the Russian Federation, based on its successful experience with fast reactors such as the BR-10, BOR-60 and BN-600, work continues on an already licensed 800 MW(e) BN-800 that can use civil and ex-weapons plutonium. According to the revised Programme for Nuclear Power Development in the Russian Federation to 2020, the startup of BN-800 at the Beloyarsk site is scheduled for 2009. Further activities in the fast reactor area in Russia include: (a) justification of a hybrid-core design for BN-600 to incinerate weapons-grade plutonium; (b) justification of life extensions for BR-10, BOR-60 and BN-600; (c) development of advanced fast reactor designs with enhanced safety (large sodium cooled fast reactor, and BREST-300 lead cooled demonstration fast reactor).

Non-electric applications:

Small and medium sized reactors are of particular interest for non-electrical application. The recently shutdown fast breeder reactor in Kazakhstan had for many years been used partly for desalination, and reactors in the Russian Federation and Eastern European countries are currently used for district heating and other process heat use. With some one third of the world's population suffering from inadequate potable water supplies, there are a number of nuclear desalination projects being planned.

- In Canada, studies include coupling desalination units to existing CANDU reactors and in co-operation with the Russian Federation to a barge mounted small ship propulsion reactor.

- Egypt is continuing its feasibility study for an electricity and desalination plant at El-Dabaa.

- In India, a desalination unit is being coupled to an existing HWR at Kalpakkam. Civil work is already under way, with commissioning expected in 2002.

- In Japan, nuclear desalination facilities are in operation with an accumulated 100 reactor-years of operating experience.

- In the Republic of Korea, a nuclear desalination unit is currently under design using a 300 MW(th) co-generating SMART reactor.

- Some countries (Indonesia, Pakistan and Tunisia) are preparing their feasibility studies on nuclear desalination under country specific conditions.

- In the Russian Federation, efforts continue on a floating power unit based on a 40 MW(e) KLT-40C reactor for multipurpose use including desalination.

2.2.3. Innovative designs for the longer term

In the USA, the newly initiated DOE Nuclear Energy Research Initiative addresses the potential long term deployment of nuclear power. In the Russian Federation, MINATOM is developing innovative fast reactor and fuel cycle concepts for a large scale use of nuclear power. Research centres in Japan, France and the EC are developing innovative reactors and fuel back-end technologies including ADS. A wide diversity of requirements and targets are used in the development of innovative reactors and fuel cycle concepts, which naturally leads to a wide variety of concepts. Table 1 indicates the likelihood of full scale commercial utilization and the expected period of use based on the opinions of some involved experts.

TABLE 1. Innovative long term reactor and fuel cycle systems

Priority	System Type	Likelihood of commercial use	Expected period of use
1	Integral nuclear fuel cycle based on dry technology	High	After 2015
2	Small-sized reactor systems for:		
	Electricity generation	High	2015
	Local heating	High	2015
	Desalination	High	2015
	Industrial heat (including hydrogen generation)	High	After 2020
3	Innovative fast reactor and fuel cycle systems	High	2020
4	Thorium based fuel cycle for fission reactors	High	2020
5	Molten salt reactors	Modest	After 2020
6	Accelerator driven subcritical systems	Modest	After 2020
7	Fusion reactors and fusion hybrid systems	Uncertain	After 2050

Under current circumstances with limited government support of nuclear research and development, there is a need for close co-ordination of R&D activities. It will require international co-operation among governmental research centres, international organizations (such as the Agency, OECD/NEA and IEA) and particularly the nuclear industry.

Joint efforts could include assessing the potential regional needs for the various applications, development of criteria and standards concerning economic, safety, long-term waste disposal and non-proliferation, and identifying the most promising concepts.

2.2.4. Energy from fusion

There is a more distant possibility for abundant energy from fusing atoms together as opposed to splitting them apart. The fusion energy released per unit of fuel is very large, about ten times greater than from fission reactions. With abundant deuterium and lithium as the primary fuels, fusion would essentially be an inexhaustible energy source. There are no atmospheric emissions and radioactive waste from regular component replacements would be comparable to fission reactors. However, disposal would be easier as very long lived radioactive substances are not produced.

Since nuclear fusion research requires complex and expensive technology, international co-operation is important to avoid duplication of effort and to facilitate the sharing of knowledge, personnel, and costs. The Agency plays an important role in co-ordinating international efforts in this area.

The European Union, Japan and the Russian Federation are designing the International Thermonuclear Experimental Reactor (ITER), which could produce about 500 MW of fusion power for many minutes. Present experiments are making good progress. The required conditions have already been produced in both magnetic and inertial confinement fusion systems. The dominant magnetic confinement concept is a ring-shaped plasma carrying a high current in a strong magnetic field, known as a TOKAMAK. For example, the Joint European Torus (JET) in the United Kingdom has already generated 15 MW of fusion power.

Since large tokamaks and stellarators are complex and expensive, requiring high-technology magnets and materials, scientists will also be trying to develop smaller “compact toroids”, which could potentially reduce the cost of fusion energy.

Large inertial confinement fusion experimental facilities under construction in the USA and France are expected to produce fusion energy yields that exceed the laser beam energy input.

Commercial scale fusion plants are not likely before mid-century. Scientific and important engineering issues remain. A demonstration system would be needed to show that reliable and economically competitive power could be developed at an industrial scale. Concerning ITER the decision on whether and where to construct it is expected in 2002.

Progress in fusion development will be discussed at the 18th IAEA Fusion Energy Conference to take place in Italy during October 2000.

2.3. SPENT FUEL AND RADIOACTIVE WASTE

Economic competitiveness would remove a major obstacle to restoring the nuclear option; nonetheless public concerns would remain. In addition to safe operation, they would centre on waste issues, partially on the safe management of spent fuel and radioactive waste principally on disposal. The worldwide trends in spent fuel and waste management are periodically summarized in status reports prepared by the Agency.

2.3.1. Spent fuel

Before either reprocessing or final disposal, spent fuel can be safely stored for long time periods in wet or dry facilities. Such facilities have in some cases already been in operation for over 30 years. About 30 tonnes of spent fuel are discharged annually per 1000 MW(e). The cumulative spent fuel discharged worldwide over the past four decades was some 220 000 tonnes by the end of 1999, with 75 000 tonnes having been reprocessed. That leaves some 145 000 tonnes stored at or away from the reactor site. By the year 2010, the Agency estimates that the cumulative amount of spent fuel will surpass 340 000 tonnes, with 110 000 reprocessed, leaving 230 000 tonnes stored (Fig. 4). Excess storage capacity worldwide is roughly 100 000 tonnes and planned construction should maintain this excess capacity over the next few decades. However, at some sites storage pools are nearing full capacity and additional storage capability is necessary.

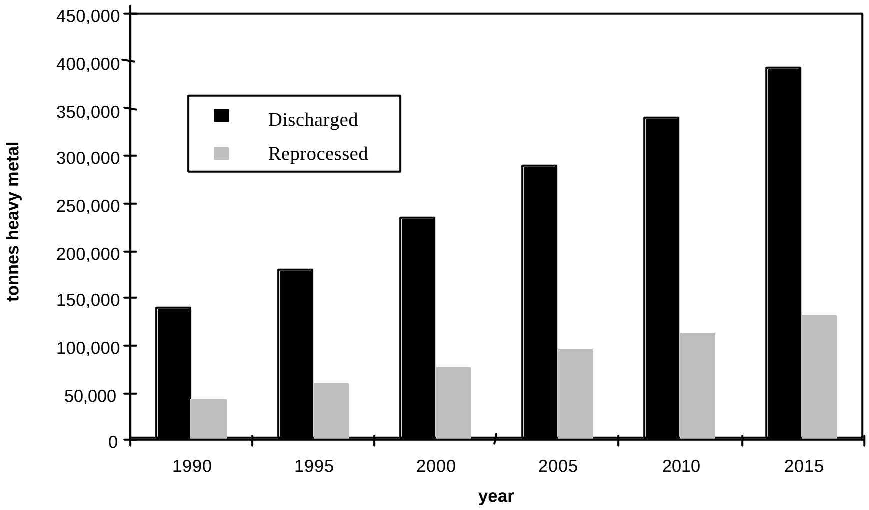


Fig. 4. Spent fuel discharged and reprocessed (1990–2015) [IAEA]

Spent fuel from research reactors, while of much lower quantity and generally of much lower radioactivity level than power reactor fuel, also requires storage and ultimate disposition. Almost 60% of research reactors are more than 30 years old, with the age of an additional 20% between 20 and 30 years. Many of the discharged fuel assemblies remain at the site, and some have already been in in-site storage for more than 30 years. Rough estimates are 63 000 fuel assemblies in storage and another 23 000 in reactor cores. Of the stored assemblies some 46 000 are in industrialized countries and 17 000 in developing countries with roughly 23 000 eligible for export back to the USA through return agreements. Much of the remaining fuel was enriched in the former Soviet Union or more recently in the Russian Federation and is generally referred to as Russian origin fuel. Negotiations continue as to the final disposition of these spent fuel assemblies.

During the past several years spent fuel in the Russian Federation from civil and military activities, particularly the decommissioning of submarines under arms reduction treaties, has received special attention. Spent fuel remains in about 100 submarines that are no longer in operation. In 1999, a Contact Expert Group set up in 1995 for international projects neared completion of a document on an *Overall Strategy for Radioactive Waste and Spent Fuel Management in the Russian Federation* to facilitate financial support for high priority projects. Financial arrangements for some priority spent fuel storage and waste processing activities have already been completed.

2.3.2. Radioactive waste

Radioactive waste disposal (including disposal of spent fuel declared as waste) is today's dominant public acceptance issue. While not involving the large quantities of gaseous products and toxic solid wastes associated with fossil fuels, nuclear power has a unique public *perception* problem: its remarkably small quantities of waste cannot be safely managed. Though not seen as a positive factor, small waste quantities in fact permit a rigorous *confinement* strategy.

The largest portion of nuclear power waste is of low and intermediate level (LILW). In the USA and France, minimization has reduced LILW to some 100 m^3 annually per 1000 MW(e), a tenfold decrease over the past 20 years. Decommissioning can add several thousand cubic metres and future efforts will likely reduce this value. While a *not in my backyard* syndrome remains, fears over LILW disposal appear to have diminished. Much of this waste is easy to manage, requiring no shielding at all during handling or transportation. It can be isolated in near surface disposal facilities where radioactive decay decreases levels rapidly, some 100 times in 200 years, reaching values comparable to natural background. More than 100 disposal facilities have been built and more than 30 are under development. These facilities also receive waste from medical, industrial and research activities. In fact, roughly 40% by volume sent to US commercial sites in 1997 was other than nuclear utility waste.

It is worth noting that in contrast to the confinement strategy for radioactive waste, the large quantities of fossil fuel waste require a *dispersion* strategy. Although varying by plant and coal type, the roughly 2.6 million tonnes of coal needed per 1000 MW(e) per year is converted into various gaseous substances that include 6 million tonnes of carbon dioxide, which is dispersed into the atmosphere. Particularly for coal, several hundred thousand tonnes of ash containing hundreds of tonnes of toxic heavy metals are often buried in shallow ground pits with only a basic soil cover. Additionally, waste can arise from noxious gas abatement procedures. Confinement would be preferable to dispersion, but is only feasible if waste volumes are small.

2.3.3. High level waste

But, the major public acceptance issue today is the disposal of high level waste (including disposal of spent fuel declared as waste), all of which is produced from nuclear power and military facilities. At the La Hague plant in France, new reprocessing procedures would convert the annual discharge of thirty tonnes of spent fuel per 1000 MW(e) into some 15 m^3 of solid high level residues (a six fold reduction over the past two decades) or some 60 cubic metres for spent fuel not reprocessed. To provide a *very rough* perspective, if the world's 10 500 tonnes of spent fuel annually could be reprocessed with equivalent volume reductions as seen at La Hague, the resulting vitrified solids would be on the order of 1000 m^3, equivalent to a cube 10 metres on each side.

No concept for long-term disposal of commercial high level waste and spent fuel waste has been licensed in any country. The scientific and technical community generally agrees that disposal can be carried out in stable geological formations that have not been disturbed for many hundreds of million years, such as in solid salt domes or granite tunnels several hundred metres below surface. Multiple natural and engineered barriers, such as metallic waste containers surrounded by absorbent clay backfill, would protect against human intrusion and ensure sufficient long term confinement for the short-lived elements to decay away, limiting any potential future release to the remaining small amounts of longer-lived elements.

Existing natural analogues provide a large degree of confidence in geological containment. Natural barriers have isolated radioactive substances for remarkably long time periods. At the Cigar Lake uranium mine in Canada, containment has been so effective that neither a chemical nor radiological indication of the ore deposit exists at the earth's surface. At the Alligator Rivers mine in Australia, uranium and its decay products have moved only tens of metres from the ore body although it is located in geological formations with relatively rapid groundwater flow. Another important analogue exists at Oklo, Gabon, where 1.8 billion years ago a spontaneous fission process in a rich uranium deposit produced radioactive substances, most of which have moved less than 2 metres from where they were formed.

While most high level waste is vitrified, research continues into ceramic waste forms that, similar to some naturally occurring minerals, are known to be highly leach resistant. These waste forms are particularly resistant to a wide range of groundwater compositions that could be found in disposal site environments. The most familiar ceramic for waste conditioning is SYNROC being developed in Australia. There are a number of SYNROC types and ceramic-like compositions under consideration as waste matrices.

2.3.4. Demonstrating geological disposal

A 1999 OECD NEA report, *Progress Towards Geologic Disposal of Radioactive Waste: Where Do We stand: An International Assessment,* provides a summary of progress over the past decade in understanding long term performance. Although emphasizing that geological disposal is technically safe, it also warns that the public remains unconvinced. The reality that high level waste disposal has not yet taken place enhances public perception that it cannot be done. Licensing and opening of disposal facilities will be the convincing demonstration that it can be done.

The opening in March 1999 of the Waste Isolation Pilot Plant (WIPP) in the USA was an important step towards demonstrating geological disposal. Located 700 metres deep in a salt formation, it is the first geological repository certified for disposal of long lived radioactive waste, principally operational waste from defence related activities. A joint IAEA–OECD/NEA organized peer review in 1997 of the post-closure performance was a factor in its certification.

In addition to the USA, several countries are currently engaged in deep disposal studies (Belgium, Canada, Finland, France, Germany, India, Japan, Sweden and Switzerland) with some having or developing underground research facilities. Nevertheless, the opening of civil waste repositories is likely more than a decade away and it will only be in a few countries. A number of developments in 1999 illustrate the progress in waste disposal:

- In the USA, in addition to progress at WIPP, a positive Draft Environmental Impact Assessment for a commercial high level waste geological repository at Yucca Mountain, Nevada, was published at mid-year. Proposed radiation safety, site suitability, and licensing requirements were also made public.

- In Finland, an Environmental Impact Assessment Report on four possible waste disposal sites was submitted in May to the regulatory body, with a decision on site selection possible late this year.

- The French Government in August authorized construction of a first underground laboratory to study deep geological disposal in a proposed clay formation. Efforts also began to site a laboratory in granite.

- In Sweden, six municipalities have shown interest in being the location for a national high level waste repository. Two will be selected this year for detailed feasibility studies.

Some differences remain concerning technically sound and publicly acceptable solutions to the high level waste issue. Long term, above ground monitored storage, permanent or retrievable disposal, international repositories and the need for transmutation of long-lived radionuclides are still being discussed. As noted later in the *Looking to the Future* section, several meetings taking place in 2000 will address these issues.

3. SUSTAINABLE ENERGY MANAGEMENT

The sustainable management of energy could become a major factor in the choice of energy options. The section reviews the rising energy and electricity demand and the projected continuing dominance of fossil fuels in the decades ahead. It also surveys uranium and fossil resources. After an update of international efforts to reduce GHG emissions that centre on the UN Framework Convention on Climate Change (FCCC), the nuclear power role in reducing emissions is examined.

3.1. RISING ENERGY AND ELECTRICITY DEMAND

The drive for clean energy sources would not be so urgent if energy needs were to remain at today's levels. But, demand will rise substantially, largely driven by economic growth in today's developing countries where 80% of the world's six billion people live. They now consume only 20% of global primary energy and almost 2 billion have no electricity. Demand will rise also due to a projected 75% growth in world population this century that will occur overwhelmingly in the developing world. The UN's latest median projection estimates a growth of 4.4 billion people by 2100.

A well recognized 1998 publication of the World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA) projects at mid-century a 100% increase in energy demand for a business as usual scenario. A low growth, environmentally driven case sees a 50% increase and a high growth case a 50% increase by 2020 and more than 150% at mid-century.

Electricity demand which globally accounts for some 35% of total commercial energy use, will grow faster than energy demand as electricity provides the greatest flexibility and cleanest energy services at the point of use. Since the early 1970s, electricity generation increased by 3.9% annually compared to 2.1% for total energy use. According to OECD/IEA 1998 World Energy Outlook, electricity continues to outpace total energy although at a somewhat slower rate (Fig. 5).

The business as usual projections of the OECD/IEA project not only a replacement of 600 GW(e) of retired capacity, but a startling doubling in the existing 3000 GW(e) of global capacity by 2020.

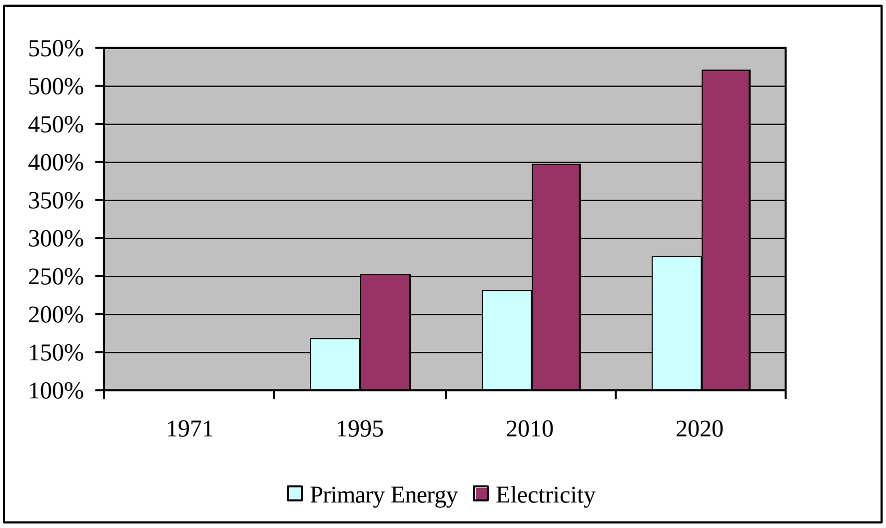


Fig. 5. Past and projected commercial primary energy and electricity growth [IEA/OECD].

3.1.1. The predominance of fossil fuels

Today, fossil fuels provide the largest portion of the world's commercial primary energy, some 87%. Nuclear and hydroelectric, both with limited environmental releases, contribute some 6% each. The non-hydroelectric renewables — solar, wind, geothermal and biomass — constitute less than 1% of the energy supply. If non-commercial energy, in many developing countries the dominant form of energy supply (agricultural residues, dung and individually collected biomass), were included, non-hydroelectric renewables would account for 11% of total energy supply. Although the fossil fuel share will decrease in the years ahead as renewables advance, the quantity used will increase due to a large growth in energy demand, and it will continue to dominate energy supply (Fig. 6).

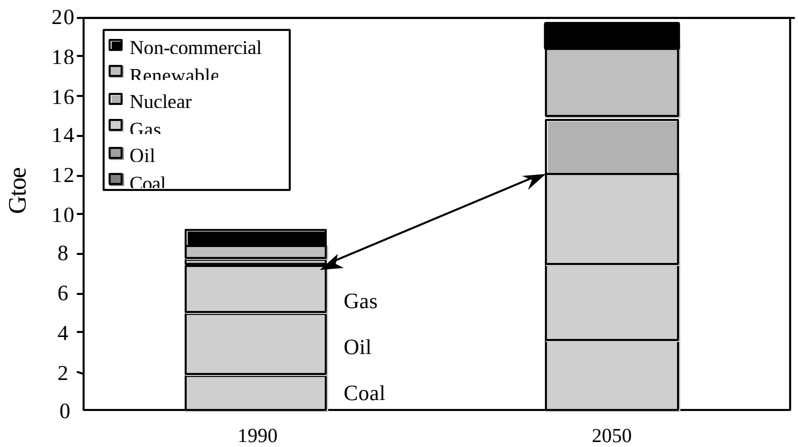


Fig. 6. Global energy (1990) and projected mix (2050) [WEC/IIASA]

For electricity generation, fossil fuels have a lesser but also dominating 63% share composed of 37% coal, 16% gas and 10% oil. The nuclear power and hydroelectric shares are 17% and 19%, respectively, with renewable systems again less than 1%. Photovoltaic cells currently make up a small .01% of world electricity generation.

The international consensus concerning the negative impacts of fossil fuel emissions could reshape the current energy mix projections. Clearly, nuclear plants as well as renewables release neither greenhouse gases, other noxious gases, nor toxic chemical substances including micron sized particulate matter.

3.1.2. Energy resources and prospects

The energy mix will likely not be driven by a shortage of any one fuel. If global consumption of the three fossil fuels - oil, natural gas and coal - were frozen at 1998 levels, conventional oil resources would be the first to approach depletion, but only after some 90 years. If consumption were to grow at 2% per year, current oil resources would last 50 years. Because oil use cannot drop to zero instantaneously, peak oil production is expected to occur within the coming two decades and global oil production start a decline – unless unconventional oil occurrences are developed (tar sands, shale oil, heavy oil, etc.) Unconventional oil could double the current oil resource base but their production economics and environmental impacts are uncertain.

Natural gas resources exceed those of oil by some 50%. Because of lower current production, their static reach amounts to more than 200 years (under 2% growth more than 100 years).

To the extent that coal proves able to substitute for oil, as a source of synthetic liquid and gaseous fuels as well as for electricity generation, fossil fuels could dominate much longer. Even if all global energy demand were met ultimately by coal, starting today, and assuming demand were to grow at 2% per year, coal *reserves* would still last more than 50 years and the coal *resource base* (reserves plus resources) would last more than 100 years.

Renewable resources, which include hydropower, biomass, solar, wind, geothermal and ocean energy, are virtually inexhaustible. Potential usable energy from these sources is difficult to estimate, but is clearly large. The economic potential of renewables hinges upon their future generating economics, especially when intermittent availability demands storage capacity, and reliability.

Known uranium resources of four million tonnes should last for over 70 years at present consumption without reprocessing. Estimates of feasibly recoverable reserves add 16 million tonnes, increasing the time period to almost 300 years. Reported uranium production has remained steady at some 35 000 tonnes annually over the past decade with roughly 50% from Australia and Canada. In these two countries, operations began in 1999 at the high grade McArthur River deposit in Canada with expected production of 4200 tonnes in 2000, and in Australia permission was granted to exploit the low grade Beverly deposit that will use an in situ leach process. During 1999, the uranium market price continued to fall and it remains low.

Reprocessing spent fuel has resulted in a global inventory of roughly 200 tonnes of separated plutonium at the end of 1999 (dismantling of weapons in the Russian Federation and the USA this decade could add an additional 100 tonnes). Using existing separated plutonium in mixed oxide fuel would extend current uranium resources more than 20 years. Fast breeder reactors that convert non-fissionable uranium into plutonium would increase the potential of today's resources by some 60 times, enough for about 4000 years at current usage. Additionally, thorium can be converted to a fissionable uranium isotope through a breeding fuel cycle. Indigenous thorium in a number of countries with limited uranium deposits could make this an attractive option.

A few countries are examining unconventional resources, such as seawater uranium and phosphate deposits, that could decouple the nuclear fuel cycle from resource depletion. While the seawater concentration is extremely low, the contained uranium is vast — roughly 4 billion tonnes. Ten per cent of this could support 1000 GW(e) of nuclear capacity for some 2000 years. Recent French and Japanese studies suggest that recovery costs could be roughly $100 per kg of uranium. Although almost four times the current price, it would contribute only several per cent to the cost of a kilowatt-hour of electricity.

3.2. THE CLIMATE CHANGE DEBATE

With fossil fuels currently responsible for some 75% of human-made emissions of carbon dioxide (CO_2), the possibility of global climate change with significant environmental consequences has alarmed policy makers. The IPCC has warned that even an implausible continuous 2% annual decrease in developed countries' emissions would not lead to CO_2 stabilization in the decades ahead due to projected increases from developing countries. Realistically, only slowing the rate of increase is possible to allow ecosystem adaptation to climate change. A *Third Assessment Report* from the IPCC in 2001 will update climate projections and provide details on possible regional effects.

Despite commitments made in the FCCC (the central climate change agreement) to reduce emissions to 1990 levels by 2000, more than half of the developed countries exceeded 1990 emissions by at least 10%. Final values are not firmed up, but the WEC has warned that the aggregate increase could be more than 8%. Recent DOE projections in the USA point to global emissions in 2020 that are some 70% above 1990 levels, with four-fifths of the increase due to expanding energy needs in developing countries.

The Kyoto Protocol, adopted at the Conference of the Parties to the FCCC -3 (COP-3) and not yet in force, strengthened the response to climate change with new targets that call for at least a 5.2% reduction on 1990 emission levels during a 2008–2012 "commitment window", instead of a return to 1990 levels by 2000. As most countries are in fact already above 1990 levels, cuts of about 30% will be needed. The protocol contains three mechanisms (in addition to domestic emission reductions within one's own national boundaries) for developed countries to meet their targets: an international *emissions trading* scheme to buy and sell emission credits amongst developed countries, including Central and Eastern European Countries (CEEC); a *joint implementation* programme with credits for financing projects in developed countries and in the CEEC; and a "*clean development mechanism*" (CDM) to allow credits for financing emission reduction projects in developing countries.

A Buenos Aires Plan of Action, adopted in December 1998 at COP-4, set an ambitious deadline of late 2000 for finalizing issues related to the mechanisms. At the November 1999 COP-5 meeting in Bonn, there was little progress on guidelines for the various mechanisms. Decisions were postponed to COP-6 to be held at The Hague this November. There was once again no formal discussion of the potential role of nuclear power.

3.3. EMISSION REDUCTIONS AND NUCLEAR POWER

Today, non-greenhouse energy sources are a significant factor in avoiding emissions. Countries with large nuclear and hydroelectric capacity have markedly lower CO_2 emissions per unit of energy than countries with high fossil fuel shares. With nuclear power, France has over the past 30 years lowered electricity sector emissions by more than 80%. In contrast, countries with limited or no nuclear power have generally increased emissions due to dependence on fossil fuels. Currently, nuclear and hydroelectric each avoid annually some 8% or roughly 0.52 billion tonnes of carbon from energy production that would otherwise be through fossil fuels. A 1000 MW(e) coal plant emits approximately 1.4 to 1.7 million tonnes of carbon annually.

Important studies have shown the nuclear advantage in reducing emissions. All 1998 WEC/IIASA scenarios assume a considerable nuclear role over the next two decades, but varying afterwards from a twenty-fold increase to total phase out by the end of the century. A mid-1998 OECD/NEA report examined three variants of the WEC/IIASA ecologically driven scenario where a major energy share is from renewables. Variant I sees steady nuclear growth reaching 1120 GW(e) in 2050 with the avoided CO_2 equivalent an important 1.7 billion tonnes of carbon in 2050, *one third* of global energy sector emissions. The accumulated amount avoided from 1995 to 2050 is nearly 55 billion tonnes C. (Fig. 7). The opposite Variant II sees a total nuclear phase out by 2050 with the accumulated amount avoided being only some 15 billion tonnes. Variant III sees stagnation followed by rapid revival in 2020 with the accumulated amount avoided between the preceding values at some 27 billion tonnes C. This last scenario would pose a challenge to the nuclear industry to ensure maintenance of technical preparedness during more than two decades of stagnation.

The OECD has initiated a three-year project on sustainable development for an OECD Ministerial meeting in 2001. It focuses on key policy issues such as the sustainable management of natural resources and the development of clean energy technologies. The OECD/NEA is preparing the nuclear power contribution to the project.

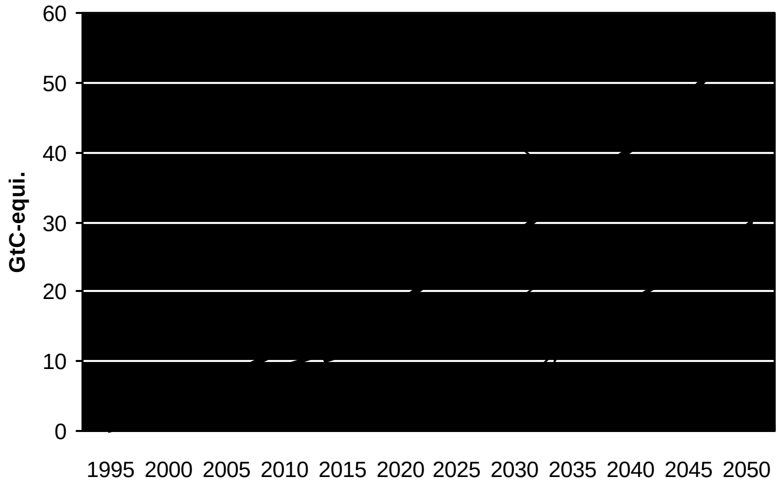


Fig. 7. Greenhouse gas emissions avoided

3.3.1. Full chain assessments

Going beyond plant operations is essential in identifying full energy chain emissions commonly ignored, such as from large fuel extraction, transportation, manufacturing and construction activities (Fig. 8). Equal electricity production requires extraction and transportation of roughly 1.5 to 3 million tonnes of oil or coal annually versus 200 tonnes of uranium fuel. Burning natural gas produces less CO_2 than burning coal or oil, but leakage during extraction and pipeline transport, more than 5% in some areas, can reduce this advantage as escaping methane is a more powerful greenhouse gas.

Hydroelectric, despite large construction activities, generally shows low emissions, but if released methane gas from decomposing organic material at the base of some reservoirs is considered, hydroelectric emissions can also reach significant values. Nuclear and wind are clearly on the very low side of emissions, while solar photovoltaic full chains are higher owing to greenhouse gases released from silicon chip manufacturing. Although biomass emissions can be low or even zero, a full chain analysis is extremely complex and currently provides uncertain results as biomass emissions involve non energy byproducts as well as growth and harvesting time periods.

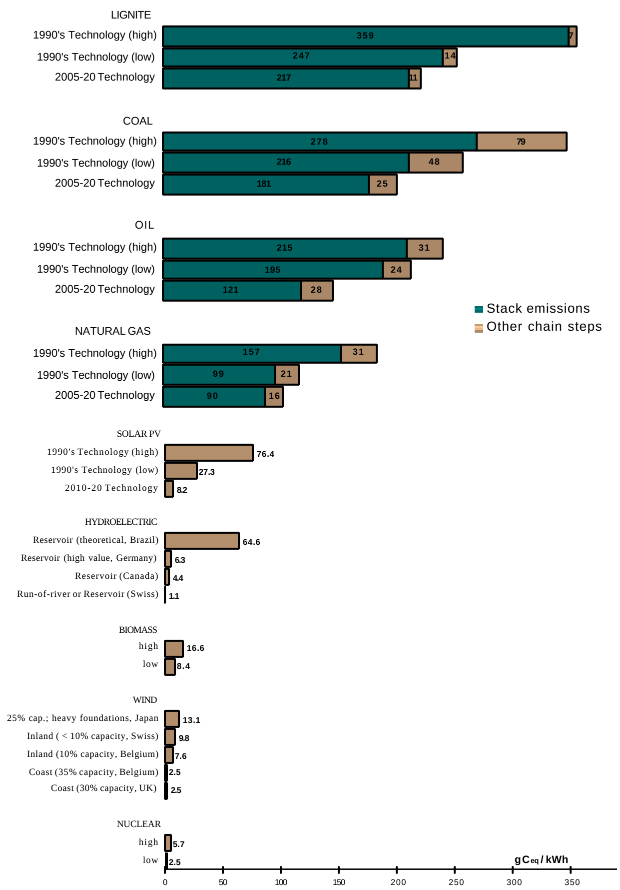


Fig. 8. Full chain CO_2 equivalent emission factors in gC_eq. / kWh[IAEA]

3.3.2. Alternative energy options

Renewables are also an option that could help avoid GHG, but their potential is difficult to fix as they are emerging technologies and not currently suitable for large baseload electricity demand. Basic challenges remain to reduce costs, improve efficiency and reliability, solve electricity storage problems and integrate them into existing energy systems. Both the WEC and IEA project they will not economically compete for large scale use in the foreseeable future and will play only a limited role in the decades to come. The WEC contends that even with adequate support and subsidies the renewables share in global energy supplies would be some 5% by 2020. The full development of small hydro systems would be needed to even maintain the hydroelectric share at its current 6% level.

The large scale use of renewables is restrained by vast land area requirements and large material needs with subsequent environmental impacts. Solar photovoltaic parks would encompass at least some 10 km^2 for 1000 MW(e), and manufacturing of cadmium/tellurium based cells would require some 60 tonnes of cadmium and 90 tonnes of tellurium. For wind fields the land requirements could climb by a factor of five and create siting difficulties.

Taking all these factors into account — rising demand, resource constraints, potential alternative technologies, and environmental impacts — the latest statement of the WEC concludes that "Nuclear power is of fundamental importance because it is the only energy supply which already has a very large and well-diversified resource (and potentially unlimited resource if breeders are used), is quasi-indigenous, does not emit GHG, and has either favourable or at most slightly unfavourable economics. In fact, should the climate change threat become a reality, nuclear is the only existing power technology which could replace coal in baseload." For these reasons, nuclear R&D is one of the priority research domains that is emphasized, stressing research on evolutionary plants, on inherently safe revolutionary designs, and on storage, waste treatment and disposal.

4. LOOKING TO THE FUTURE

4.1. A SURVEY OF UPCOMING EVENTS

The Agency's Medium Term Strategy (MTS) defines five Agency goals for 2001–2005. The upcoming events cited in this section address principally the first of the MTS's three substantive goals, i.e. "Enhancement of the contribution of nuclear technologies towards meeting, in a sustainable manner, the needs and interests of Member States", plus the first of its two functional goals, i.e. "Effective interaction with partners and the public." We begin with the increasing attention being given to sustainable energy management, followed by economic competitiveness, advanced nuclear technologies, waste management, communication and concluding with international co-operation.

4.1.1. Sustainable energy management

4.1.1.1. *Sustainable energy discussions*

The sustainability credentials of nuclear power still have not been fully reflected in energy debates. Major UN meetings will take place in April 2001 when the Commission on Sustainable Development (CSD) focuses on energy at CSD-9 and in 2002 with Rio Plus Ten, the follow up to the 1992 UN Conference on Environment and Development. As already requested, the Agency will provide background material to CSD-9, which could include the *Nuclear Technology Review 2000*, to foster an open and frank exchange of views between its Member States and among other international organizations. The Agency is also prepared to respond to requests from the Rio Plus Ten conference.

In November, COP-6 will continue discussing mechanisms for greenhouse gas emission reductions. Although there were interventions at COP-5 about a nuclear role, there was no formal debate and it remains to be seen if nuclear is included as a *clean and sustainable technology* within emission reduction schemes, such as the CDM that allows credits for developing country projects. The Agency will continue to assist in country assessments that could be useful in the debate. Additionally, a *Special Event* on nuclear issues is being considered, as was done at COP-3 in Kyoto. Amongst others, UNDP, WHO, WMO, UNEP and IEA will likely be involved with special events. A Special Event can be done in conjunction with others.

The IPCC is near to finalizing a Third Assessment Report on climate change and a Special Report on Emission Scenarios, that includes nuclear, for use in future climate change, mitigation and impact analyses. The Agency will continue to follow their preparation and provide appropriate input on the nuclear role in avoiding GHG emissions.

4.1.1.2. *Comparative assessments*

Decision making in the energy area requires objective comparative analyses that include full energy chain economic and environmental factors. The Agency has developed extensive databases and computer tools for such analyses that have been used in some ninety countries. Efforts to update data and assist organizations in their analyses will continue. A report will soon be issued on full energy chain GHG emissions that shows the nuclear advantage of low fuel requirements and consequently low mining and transportation activities.

The Agency will also keep abreast of the already noted ISO evaluation of a *Life Cycle Impact Analysis* for judging the influence of air emissions, waste and land use on energy options.

4.1.2. Economic competitiveness

4.1.2.1. *Market liberalization*

Energy market liberalization is continuing globally with competitiveness remaining a decisive factor. The Agency will soon release and widely distribute a document on *Strategies for Competitive Nuclear Power Plants* directed at existing plants and plants under consideration. It should be particularly useful in ongoing assistance to among others, Egypt, Indonesia, Morocco, Thailand and Turkey, who are discussing a nuclear role in their energy mix.

Energy market liberalization will also affect technology choices for new generation plants. How these choices will be made and how they can be accommodated is a matter of ongoing study in many countries.

4.1.2.2. *Plant performance and life extension*

With life extension becoming routine in many countries, assessments and procedures for assuring the performance and safety of ageing plants are growing in importance. The Agency will continue to prepare recommendations through its activities and continue development of a technical database for monitoring and surveillance of major plant components and structures.

Through technical assistance efforts, the Agency will help advance an integrated management approach that considers not only the technology, but factors such as financing, environmental considerations, human resources, regulations and public acceptance. The approach also recognizes that improved plant performance and economics leads to increased safety.

Regional sharing of experience has been an important contribution to transition countries of Eastern Europe and the former Soviet Union in improving human resource management, in-service inspection and plant life management. High priority will continue to assistance activities in this area, taking into account bilateral efforts as well as those of the EU and OECD/NEA.

4.1.2.3. Internalization of costs

As already described, there are signs of a global trend to pass on to the polluter the cost of environmental externalities. As it relates to the nuclear power debate, the Agency will remain ready to co-operate with organizations such as IEA and OECD/NEA in assessing the cost implications of the various environmental and health impacts of energy production.

4.1.3. Advanced reactor technologies and fuel cycles

A nuclear power revival is linked by some to innovative reactors including accelerator driven systems that could feature better economics, proliferation resistance, waste minimization and inherent safety. The Agency is currently exploring initiating an international project to facilitate information exchange and foster a forum for discussions of innovative reactor technologies.

In 1999, a symposium on MOX fuels examined options for civil and weapons plutonium and also diversion resistant fuel cycles producing non-weapons grade plutonium along with uranium-thorium fuel cycles producing less plutonium and a fissionable uranium isotope denatured by non-fissionable uranium. Currently, a technical group on nuclear fuel cycle options supports some Agency activities in this area.

Efforts will also continue to facilitate exchanges on advanced reactors in general. A number of technical group meetings, such as on gas, water and liquid metal cooled reactors, will take place during the next two years to discuss technology and performance developments along with assistance activities.

The Agency has the intention to initiate the establishment of a Task Force on innovative nuclear reactors and fuel cycles. At present work is proceeding at the national level in several Member States on new approaches to nuclear power reactor design and fuel cycle concepts. In some cases, however, national research and development programmes are carried out in relative isolation, with insufficient account being taken of global user requirements and related activities in other countries. Furthermore, available research and development funds are often limited, thus reducing the chances of success of potentially promising initiatives.

These national activities, and the desirability for co-ordinating them internationally, have been acknowledged at several meetings held under the auspices of the IAEA. The IAEA Scientific Forum (September 1999), the Advisory Group Meeting on *Development of a Strategic Plan for an International Research and Development Project on Nuclear Fuel Cycles and Power Plants* (October 1999), and the Industry Forum (January, 2000) are recent examples. These meetings have recommended that the Agency take steps to facilitate assessment of the potential for, and exchange of information on, innovative nuclear reactors and fuel cycles. Several Member States have made similar suggestions to this end.

4.1.4. Waste management

4.1.4.1. *High level waste*

As already noted, differences exist concerning technically sound and publicly acceptable answers to the waste issue. Long term above ground storage, permanent or retrievable disposal, remote area disposal and international repositories are some issues still being discussed. In addition to an international *Conference on the Safety of Radioactive Waste Management* that took place in Spain during March 2000, the Scientific Forum at the General Conference in September 2000 will centre its discussion on the waste issue.

The Agency will also co-operate with the Material Research Society's international symposium this year in Australia on the *Scientific Basis for Nuclear Waste Management*. An Agency Research Co-ordination meeting will also be held on the chemical durability under repository conditions of various waste conditioning methods including SYNROC.

4.1.4.2. *Decommissioning*

Decommissioning activities will increase as ageing and non-competitive plants are shut down. Internationally agreed criteria being developed that permit materials with little contamination to be treated as non-radioactive waste will have a significant impact on the amount of waste requiring disposal. The Agency will participate in meetings over the next two years that consider the revised criteria.

The Agency is also cooperating with the US Department of Energy in organizing the fourth *International Decommissioning Symposium* to be held in June 2000 at Knoxville, Tennessee.

4.1.4.3. *Naturally occurring radioactive material (NORM)*

Activities, such as mining and mineral processing, oil and gas extraction and coal and geothermal energy sources, can produce large amounts of wastes with technologically enhanced concentrations of naturally occurring radioactive material (TE-NORM). Although not covered in this Review, the disposal of these wastes is an emerging concern as the radionuclides are long-lived. The Agency will continue to support workshops in countries of Africa, Asia and the Pacific where exploitation of natural resources is a dominant industry.

Also in Africa and Asia, activities for conditioning spent radium sources from medical use will continue. A similar programme is almost finished in Latin America.

4.1.5. Dialogue and communication

Civil society is increasingly influencing national and international energy policy in both the developed and developing world. The Agency can promote a dialogue and provide balanced and factual information for decision making. An Industry Forum was held in late January at the Agency and two regional seminars are scheduled, one in April on the *Peaceful Uses of Nuclear Energy in Central and Eastern Europe* to take place in Hungary and another on *Waste Management and Site Restoration* in Romania during September.

Other events being considered to foster discussions are a special public information seminar in Mexico focusing on the management of radioactive waste and seminars in Latin America and in Africa.

4.1.6. Trends in international cooperation

4.1.6.1. *Information exchange*

An international symposium on the *Uranium Production Cycle and the Environment* will be held at the Agency in October. Based on responses from 29 countries, a joint report was prepared in 1999 by the Agency and OECD/NEA on *Environmental Activities in Uranium Mining and Milling* that was the first on the subject.

The Agency is organizing an international seminar on the *Status and Prospects for Small and Medium Sized Reactors* in 2001 and is also cooperating with the international conference on the *Nuclear Option in Countries with Small and Medium Electricity Grids* to be held this June in Croatia.

In the broader based nuclear meetings, the Agency is co-operating with the 12th Pacific Basin Nuclear Conference to be held in the Republic of Korea in October and the 8th international conference on Nuclear Engineering (ICONE-8) in the USA.

Three international meeting on radioactive waste management in the year 2000 are in co-operation with the Agency: *Waste Management 2000* which took place in February in the USA; *Dis Tec* 2000 to be held in Germany in September; and *Safewaste 2000* to be held in France in October. For the many countries that are increasingly involved with non-power issues the Agency is planning an international seminar on *Radioactive Waste from Non-Power Applications: Sharing the Experience* to be held in 2001.

There is a growing use worldwide of electronic information on the Agency's Internet home page, such as through the Power Reactor Information System (PRIS). There will be increased nuclear power and fuel cycle information made available on the Internet for the technical and non-technical audience.

4.1.6.2. *Activities of other international bodies*

UNDP, UNDESA and WEC are preparing a *World Energy Assessment* as input to discussions at CSD-9 and the Rio Plus Ten conference. The Agency has provided input and participated in several reviews of the report to encourage and support a balanced presentation of the nuclear issues.

As mentioned in this Review, the OECD/NEA is preparing a document on nuclear energy in a sustainable development perspective as part of its work programme.

WEC is preparing publications that will be useful for Agency activities and planning efforts, such as *Pricing Energy in Developing Countries* and *Energy: The Ethical Dimension*. The WEC in its *Statement 2000* continues to support nuclear power, particularly for global warming strategies. Generally, the Agency is ready to increase its involvement with organizations requiring factual material on the nuclear option.

The WANO completed its 100th peer review in 1999 to check the performance of nuclear plants worldwide. It publishes a set of plant performance indicators, as does the Agency. Continuing contacts between the two organizations are mutually advantageous.

4.1.6.3. *Maintaining human and technical resources*

With stagnation in many countries, maintaining the nuclear power infrastructure is a concern. In Western Europe and North America, the number of educational institutions training students for the nuclear industry has decreased. In the USA, statistics show a more than 60% decrease from the 1800 nuclear engineering enrolments in 1979. Skills and knowledge still exist, partly maintained through the service industry, but they could be in scant supply with a nuclear renewal.

Also in the USA, the government announced some $22 million in funding for the Nuclear Energy Research Initiative to maintain the nuclear option through various activities, such as research on advanced reactor and fuel cycle technologies, and support to maintain a nuclear science educational infrastructure. This initiative and recent international industry mergers may lead to a more focused look at the issue.

The Agency's contribution to maintaining the nuclear option will continue through the collection and dissemination of scientific information and the transfer of technology, particularly to developing countries.

APPENDIX 1. OPERATING NUCLEAR POWER PLANTS: Number of Reactors in Operation by Region and Type

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Region	Type	No.	Total MW(e)	Years in Operation
Africa				
	PWR	2	1 842	30
	Total	*2*	*1 842*	*30*
Eastern Europe				
	FBR	1	560	45
	LWGR	18	13 514	424
	PHWR	1	650	3
	PWR	1	632	18
	WWER	47	29 953	772
	Total	*68*	*45 309*	*1262*
Far East				
	ABWR	2	2 630	7
	BWR	30	25 346	531
	FBR	1	246	5
	HWLWR	1	148	21
	PHWR	4	2 579	22
	PWR	40	32 783	567
	Total	*78*	*63 732*	*1153*
Latin America				
	BWR	2	1 360	16
	PHWR	2	935	43
	PWR	1	626	18
	Total	*5*	*2 921*	*77*
Middle East and South Asia				
	BWR	2	300	61
	PHWR	10	1 722	135
	Total	*12*	*2 022*	*196*
North America				
	BWR	35	32 099	45
	PHWR	14	9 998	424
	PWR	69	65 046	1540
	Total	*118*	*107 143*	*2009*
Western Europe				
	AGR	14	8 380	250
	BWR	20	17 699	564
	FBR	1	233	86
	GCR	20	3 400	1094
	PWR	93	95 406	1642
	WWER	2	976	97
	Total	*150*	*126 094*	*3733*

World Total	*433*	*349 063*	*8460*

APPENDIX 2. LIST OF ABBREVIATIONS FOR REACTOR TYPES

ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-cooled Reactor
BWR	Boiling Water Reactor
FBR	Fast Breeder Reactor
GCR	Gas Cooled Reactor
HTGR	High Temperature Gas Reactor
HWLWR	Heavy Water-moderated Light Water-cooled Reactor
HWR	Heavy Water Reactor
LWGR	Light Water Gas-cooled Reactor
PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
WWER	Water-cooled Water-moderated Energy Reactor

Part II: Nuclear applications

INTRODUCTION

The emergence of fission reactor technology and nuclear power for electricity generation during the second half of the 20th century was the outcome of substantial basic and applied research in the fields of physics, chemistry, engineering and electronics, among others. Many of the products and much of the intellectual capacity required for this research and development effort also paved the way for advances in research reactors and accelerators, which are powerful sources of ionizing radiation for a variety of applications, and are also used extensively for radioisotope production. Concurrently, a variety of specialized instrumentation has been developed to use these special tools of nuclear science. All applications of nuclear sciences are either based on the interaction of ionizing radiation with matter or the use of isotopes as tracers to study physicochemical and biological processes. These applications span a large spectrum of activities, from the basic human needs of food, water and health to the developmental needs in the form of most modern, environmentally benign, industrial processes.

This part, the first review of its kind by the Agency on the status of and significant developments in a broad range of non-power nuclear technologies, focuses primarily on applied nuclear sciences that contribute towards achieving economic, social and development goals. It begins with developments in those areas of nuclear science which form the common basis of other applications, namely nuclear reactors, accelerators and nuclear instrumentation, which are sources of ionizing radiation and radioisotopes or are essential for various measurements. These technologies are grouped under five broad areas representing enduring human concerns. The review ends with a look at the current status of fusion energy research and the possible future development of fusion as a viable technology for energy generation.

With research and development and continuous innovation in applied nuclear sciences expected to continue, as well as an expansion in the use of nuclear techniques to meet existing and new challenges, there is confidence that nuclear technology will play an increasingly important role in sustainable human development, be it in food production and agriculture, management of scarce water resources, improving health, developing efficient and innovative industrial processes, or in the protection of the environment. The Agency continues to facilitate internationally co-ordinated research and technical co-operation between its Member States to strengthen R&D capacities and enhance technology transfer.

5. BASIC TOOLS FOR NUCLEAR APPLICATIONS

5.1. RESEARCH REACTORS, ACCELERATORS AND RADIOISOTOPES

5.1.1. Current Status and Achievements

Research reactors and accelerators are powerful tools of nuclear science and serve as sources of ionizing radiation for materials investigation and for radioisotope production. They have had a significant impact on economic and industrial development in many countries and have facilitated the development of high technology products. They have also contributed significantly to health care. While many old reactors have been shut down worldwide, a number of countries have operating research reactors and more are being built. Accelerators, which in the beginning were delicate machines for experiments in nuclear physics, have matured into reliable tools that are now used in industrial processes and health care.

5.1.1.1. Research Reactors

Research reactors are the main engines of progress in nuclear science and technology. They are crucial for any country embarking on a nuclear power programme to build expertise in disciplines like neutronics, thermophysics, thermodydraulics, radiation physics and reactor related materials science. Research reactors are also important in non-power applications as they are used in isotope production, neutron activation analysis, semiconductor doping, neutron radiography and radiation therapy, as well as in education and training. Research and development in many areas of science, including physics, chemistry, biology, medicine, geology and environmental sciences is dependent upon research reactors. According to the Agency's Research Reactor Database, 58 countries, including 40 developing countries, operate 293 research reactors, and 15 more are under construction. Currently, almost 60% of operating research reactors are over 30 years old, and many are approaching decommissioning, so the ageing of components is becoming a serious issue. Following the steady downward trend since the mid-1970s, 39 reactors have been shut down and 11 new ones commissioned over the past five years.

5.1.1.2. Accelerators

Thousands of low energy particle accelerators are in operation around the world. With their increasing reliability and versatility, particle accelerators are now being used in a variety of fields, as shown in Table 2. The majority of the electron accelerators are found in industry with applications such as cross-linking of plastics, flue gas treatment and sterilization of food and medical supplies. They are used widely in hospitals for the treatment of cancer, and small dedicated cyclotrons are used for producing isotopes for diagnostic as well as therapeutic purposes. Ion accelerators are used in the electronics industry for implanting atoms onto the surface of semiconductor materials. Ion implantation is also used for hardening the metal surfaces of medical implants. Ion beam analysis (IBA) techniques using low energy electrostatic accelerators, including accelerator mass spectroscopy (AMS), can detect and quantify elements with sensitivities down to one part per trillion and with a spatial resolution of about 0.1μm. Instruments based on small, sealed tube electrostatic neutron generators are used to interrogate concealed objects by inducing nuclear reactions and measuring the energy and intensity of the emitted gamma rays in order to determine the relative abundance of various elements. Applications of this technique include oil and mineral prospecting, control of industrial processes and the identification of explosives and chemical warfare agents.

TABLE 1. Selected applications of particle accelerators.

Type of accelerator	Energy (MeV)	Number	Applications	Uses
Ion accelerators				
Neutron Generators	0.1 – 3	Data not available	Neutron activation analysis Applied neutron research	Well logging Industrial process control and analysis Detection of explosives and drugs Cancer treatment
Ion Implanters	< 3	7000	Ion beam treatment of materials Applied research in the area of ion beam synthesis and processing of advanced materials	Computer chips Wear and corrosion resistance Human joint implants Synthesis of nanoclusters, nanowires, and layers Ion beam induced slicing Formation of metastable materials
Low–Medium Energy	< 100 <100 < 100 < 300	>100 ~10 >200 20	IBA and AMS Applied research to material science, biology, medicine, geology, climatology, etc. Production of nuclear filters Production of radioisotopes Medical treatment Nuclear Physics Research	Trace element detection Dating Two and three dimensional mapping of elemental concentration profiles and some material properties Separation Technology Medical diagnosis and therapy Cancer therapy Experiments with radioactive beams
Spallation Neutron Sources	~ 1000	~ 10	Applied Research in material science, biology, medicine, chemistry	High-tech materials development Investigating structure of different materials Nuclear waste transmutation
Electron accelerators				
Low–Medium Energy	< 50 0.1-1.5 5, 10	~6000 1000 30	Hospitals Radiation processing Radiation processing	Cancer therapy Surface coating, curing Improvement of materials Environmental applications Medical equipment sterilizaation Food preservation Polymer modification

Synchrotron Radiation Sources	~ 1000	~ 50	Applied Research in material science, biology, medicine, chemistry	Materials Life sciences

5.1.1.3. Radioisotopes

Radioisotopes meant for medical or industrial purposes are produced in reactors or accelerators and processed in hot cell facilities. A survey by the OECD/NEA and the Agency published in 1998 on the beneficial uses and production of radioisotopes shows continuous and steady application of isotopes in various sectors, indicating that they remain in many cases among the best techniques available and are an economically attractive option. The status of production facilities around the world is as follows:

- 75 research reactors;
- 48 accelerators dedicated to medical isotopes;
- 130 additional cyclotrons dedicated only to positron emission tomography (PET);
- 10 non-dedicated accelerators producing radioisotopes;
- 10 nuclear power reactors producing cobalt-60;
- 50 countries with processing facilities.

A number of countries produce radioisotopes to meet their domestic requirement. Countries which are major international suppliers of radioisotopes, particularly molybdenum-99, include Canada, Belgium and South Africa. The number of research reactors used for isotope production is decreasing, particularly in developed countries. However, the need for a secure supply of isotopes for sustaining critical activities in medicine and industry has been acknowledged and the first two dedicated isotope production reactors are under construction in Canada. The number of cyclotron facilities, particularly those dedicated to radioisotope production, has increased steadily over the past thirty years. Increasing attention is being paid to meeting radiation safety standards and internationally accepted quality assurance practices in isotope and radiopharmaceutical processing facilities.

Radiopharmaceuticals based on technetium-99m, thallium-201 and iodine-131 account for the principal application of radioisotopes in the medical field, with demand growing by 5% per year. Gamma imaging has a global turnover of around $1 billion with 80% of use concentrated in North America, Western Europe and Japan. About a dozen private companies and several state institutions currently produce and supply radioisotopes. Fluorine-18 is the principal radioisotope used in 90% of all PET imaging, with other short lived radioisotopes such as carbon-11, nitrogen-13 and oxygen-15 used to a lesser extent. This field is growing by about 15% each year, but is still largely confined to the developed countries. Radiotherapy using radiopharmaceuticals is used mainly for treating hyperthyroidism, synovitis and certain types of cancer. Strontium-89, samarium-153 and rhenium-186 are being used for the palliative treatment of cancer with an annual turnover of approximately $28 million. An important requirement for the production of radioisotopes using cyclotrons is the availability of stable isotopes for the manufacturing of targets.

Radioimunoassay (RIA) is a very sensitive and specific in vitro method that is used mainly in medical analysis. In developed countries, RIA is being progressively replaced by non-radioactive immunoassays, but in developing countries the use of this method is steady or increasing, owing to the fact that it is robust, less expensive and suitable for technology transfer.

Sealed radioactive sources are widely used in teletherapy and brachytherapy of cancer. Other applications of sealed radioactive sources are found in industry and isotope power sources. There is a modest demand for a variety of sources for such applications as nucleonics, radiography and industrial irradiation. Small sources are also used in smoke detectors.

5.1.2. Future Trends

5.1.2.1. Research Reactors

There is a trend to close some small research reactors in advanced countries and to build a few high flux reactors for specific purposes. While many old research reactors have been shut down, more facilities are being planned or are under construction now than at any time in recent history. Most of these new reactors are of higher power, of a few megawatts or more. Multipurpose reactors are under construction in Morocco (2 MW) and Thailand (10 MW) and the new HANARO (30 MW) facility is operating in the Republic of Korea. These reactors have capabilities for radioisotope production, neutron radiography, neutron activation analysis, boron neutron capture therapy and extracted beam research. New facilities are also being planned for very specific purposes. For example, the 20 MW FRM-II reactor in Germany will provide advanced beamlines for neutron scattering research and for research in areas like medicine and biology. Two MAPLE 10 MW reactors in Canada are dedicated isotope production facilities. The 100 MW French reactor 'Jules Horowitz' will be used for testing fuel and materials. And in Australia a new multipurpose reactor for neutron beam research and radioisotope production is planned for operation by 2005.

5.1.2.2. Accelerators

Synchrotron are strong sources of radiation in wavelengths ranging from infrared radiation to X rays, emitted by high energy electrons circulating in a ring and interacting with special magnet systems. Synchrotron radiation is used in macromolecular crystallography to locate the position of atoms in large protein molecules. This facilitates understanding of the human genome and the design of new anti-viral drugs. Synchrotron light also supports photolithographical techniques for manufacturing mechanical parts down to the size of hundredths of a millimetre — nanotechnology — with potential applications in the automotive industry and in the design of medical devices. There are 45 operating synchrotron light sources, 11 under construction and 16 proposed in 20 different countries around the world.

Protons accelerated to several GeV (billion electron volt energies) impinging on a heavy metal target produce neutrons by 'spallation'. Spallation neutron sources are finding increasing use in neutron scattering experiments to study the structure of advanced materials. In the future they could also be used for the transmutation of long lived isotopes in nuclear waste. These sources are also being studied for their potential for electrical power generation when combined with a subcritical reactor core of thorium. Heavy ion accelerators with GeV energies and very high beam currents are being studied to compress deuterium–tritium pellets for self-sustained thermonuclear fusion. There has also been increased interest in dedicated 200–300 MeV proton synchrotrons for the conformal treatment of discrete tumours.

5.1.2.3. Radioisotopes

The development of new medical applications may create additional demand for isotopes. Significant areas are likely to be nuclear imaging, particularly PET and radiotherapy.

The use of cobalt-60 in teletherapy is expected to decline in developed countries because of the gradual replacement of this technique by electron accelerators. However, teletherapy continues to be an important mode of treatment in developing countries. Other advances in sealed source application in medicine may increase the demand for high specific activity iridium-192 and cobalt-60 sealed sources, as well as caesium-137 and small amounts of other radioisotopes for specialist applications, such as iodine-125, palladium-103 and ruthenium-106.

An issue of concern for the future is the security of supply of isotopes, given the limited number of production facilities and the expected rise in demand. This could have an impact on the health and industrial sectors, in particular.

5.2. NUCLEAR INSTRUMENTATION

5.2.1. Current Status and Achievements

Nuclear instrumentation is a key element in the infrastructure for the development and application of nuclear techniques in both developed and developing countries, affecting radiation counting and spectrometric systems, X ray fluorescence and diffraction systems, single photon emission computer tomography and PET cameras for medical imaging and systems for cancer therapy. It is an area of rapid innovation, which results in the availability of new instruments and equipment in the market and in a high rate of obsolescence. Advances in nuclear instrumentation include new radiation detectors, digital signal processing equipment, increased use of instrument control by microprocessors and personal computers, use of neural network data analysis systems, and surface mounted techniques. Some of the more significant recent developments are listed in Table 3.

TABLE 2. A selection of significant developments in nuclear instrumentation

- Room temperature radiation detectors, in particular for monitoring radioactive and non-radioactive pollutants, and for use in nuclear safeguards;
- Portable instruments for in situ gamma and X ray spectrometry with low energy consumption and miniaturized electronics based on very large scale integration elements;
- Position sensitive detectors in high energy physics and spectrometry;
- Applications of microprocessor and microcontroller based instrumentation;
- Nuclear instruments based on the surface mounted technique, which provide more reliable and compact components;
- Instruments based on field programmable logic arrays and application specific integrated circuits;
- Networking of nuclear instrumentation.

5.2.2. Future trends

Nuclear instrumentation will continue to evolve along the lines indicated in Table 3. Increased integration of electronic circuit boards is foreseen and significant changes in the training programmes for electronics engineers and technicians will be needed. Instruments will be more easily maintained and operated and troubleshooting will increasingly be supported by modern telecommunications techniques. However, training in the calibration, maintenance and repair of instruments based on older, more conventional electronics will still be needed in some developing countries.

5.3. NUCLEAR DATA

5.3.1. Current Status and Achievements

Nuclear data describe the properties of atomic nuclei, such as gamma ray energies from radioactive decay and the cross-sections (probabilities) of nuclear reactions, such as neutron induced fission. These data are essential for applications including nuclear power, nuclear safeguards, nuclear medicine and activation analysis. Scientists working in these and realated areas need to retrieve large quantities of numerical data each day from nuclear data centres for their work.

Expensive and demanding measurements are needed to obtain nuclear data. To be useful in applications, these data must be compiled in computerized form, evaluated, formatted into data libraries and finally disseminated. This effort is shared by the international community of nuclear data specialists who have produced a single, shared, user oriented, international data repository.

This shared international nuclear database includes bibliographical references to nuclear reaction data and the numerical results of these experiments. The database is nearly 100% complete for neutron data and contains experimental data from around 10 000 publications. It is being expanded to include reactions induced by charged particles and photon induced reactions. These developments are carried out by the Network of Nuclear Reaction Data Centres, which include the Agency, the OECD/NEA Data Bank, the US National Nuclear Data Center, the Russian Nuclear Data Centres, the China Nuclear Data Centre, and the Japanese Nuclear Data Centre.

Nuclear structure and decay data are also important, and an active international effort is devoted to producing and maintaining the Evaluated Nuclear Structure Data File (ENSDF). ENSDF presently contains information on over 2800 nuclides, including over 150 000 distinct gamma ray "lines". This work is carried out by the Network of Nuclear Structure Data Centres, including the Agency (network co-ordination), the US National Nuclear Data Center (master database), and 17 data evaluation groups around the world.

5.3.2. Future Trends

Because of the high cost and complexity of nuclear data experiments, available resources have been focused in the past on those data of importance for specific applications, such as data needed for the design of present-day nuclear power plants. Requirements for state-of-the-art analyses of the safety and environmental impact of nuclear facilities have led to demands for more detailed information in the nuclear data files and for better estimates of data uncertainties, which are often lacking. Another emerging need relates to the assessment of criticality in centralized spent fuel storage facilities, taking into account the effect of accumulated fission products in the fuel. Looking to the future, initiatives to close the nuclear fuel cycle will require much more detailed knowledge of the nuclear data for the isotopes of neptunium, americium and curium.

Similarly, the quality and coverage of nuclear data is often a limiting factor in emerging non-power nuclear applications, so the generation of new data plays a catlytic role here as well. For example, in the field of radiotherapy, nuclear and atomic data libraries provide the basis of new all particle transport calculations which help maximize the radiation dose delivered to tumours, while limiting the dose to surrounding healthy tissue. Very detailed cross-section data and gamma-ray energy spectra are needed in new methods of material analysis, such as prompt gamma-ray neutron activation analysis. Developments such as these will continue to generate new requirements for nuclear data measurements and internationally co-ordinated activities to incorporate these data into the shared international database.

6. NUCLEAR TECHNIQUES BY FIELD OF APPLICATION

6.1. FOOD SECURITY AND SUSTAINABLE AGRICULTURE

6.1.1. Current Status and Achievements

6.1.1.1. Crops and Cropping Systems

There have been advances in the development and application of isotopic techniques to estimate the dynamics of nutrients and water in the soil–plant system. Natural variations in the abundance of the stable isotope carbon-13 have been used to estimate rates of turnover of soil nutrients and organic matter, and to identify plant genotypes with high efficiency of water use and drought tolerance. Similarly, using natural variations in the abundance of the stable isotopes of oxygen and hydrogen has enabled sources of water transpired by trees to be identified. These techniques are being used to test and develop agroforestry systems and tillage practices and to obtain basic information on soil processes and the physiological responses of plants to stress factors. Hand-in-hand with these developments have been advances in automated systems for the isotope ratio analysis of plant, soil and atmospheric samples by mass and optical emission spectrometry. Substantial progress has also been made in using radionuclides from fallout, such as caesium-137 or lead-210, as tracers to estimate the redistribution rates of soil and hence erosion.

Although the potential of mutation techniques as a tool for crop improvement has been known for several decades, information has come to light recently on the economic success of some mutant varieties of important crops. During the last five years alone, 112 crop mutant varieties have been officially released in 28 countries, including important crops such as rice, wheat, barley, cotton, rapeseed and soybean. Radiation induced mutations were a factor either directly or indirectly in as much as 90% of these cases. Since 1996, the use of neutrons has emerged in the molecular analysis of plants.

Methods have also been developed using in vitro facilitated, radiation induced mutagenesis for the improvement of seed propagated crops. In vitro techniques using anthers or isolated immature pollen grains can be used to shorten breeding cycles and facilitate the identification and screening of desired mutants. This can lead to the rapid development of genetically uniform breeding lines. Such a biotechnological method will increase the attractiveness and comparative advantage of mutation techniques in the breeding of — and molecular research into — seed propagated crop plants.

Some crops such as cassava, yam, potato and banana are extremely important for food security, especially in developing countries, but must be vegetatively propagated. For these crops, induced mutation is currently the only technique that can create with a high enough frequency the necessary variation for a wide range of desired agronomic characters. Research on the development of mutation techniques for the treatment of cell and tissue cultures of vegetatively propagated food crops has led to the release of new mutant varieties of cassava in Ghana and banana in Malaysia, and to the development of protocols for the radiation treatment of many crop species in various types of in vitro cultures.

The number of mass production facilities for sterile insects has increased rapidly over the past five years (Fig. 9). Fruit flies are notorious quarantine pests because of the extremely wide range of hosts they attack. The sterile insect technique (SIT) to control or eradicate this insect pest 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 programmes have been implemented in Chile, Argentina and the USA.

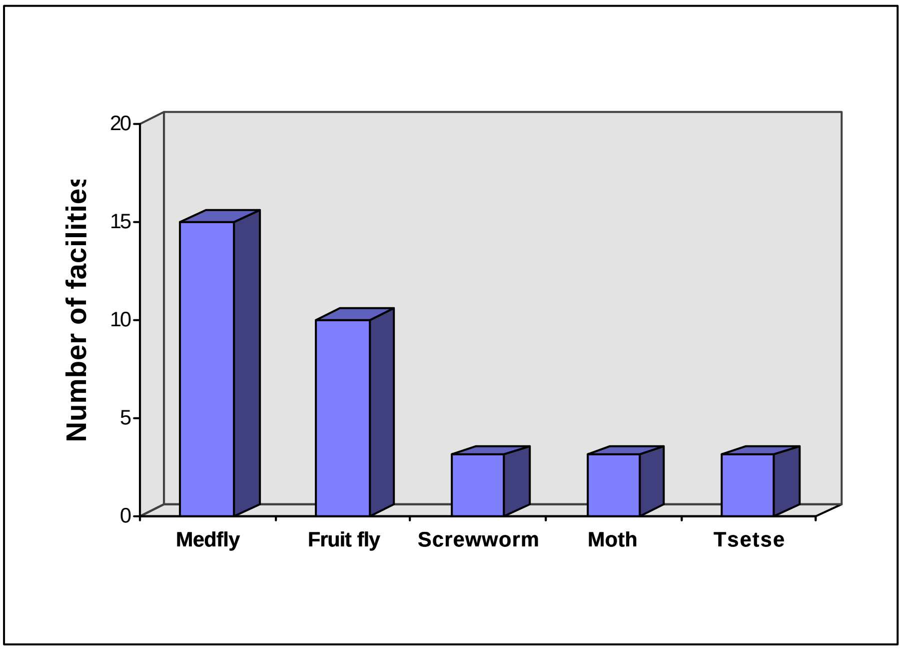

Figure 9. Current facilities in the world for the mass production of sterile insects

The most recent major advance in SIT has been the development of male-only strains of the medfly. The availability of these genetic sexing strains has enabled fly production facilities and plant protection authorities to produce and release only sterile male insects, resulting in reduced SIT costs and greater effectiveness of the released flies. This increased efficiency of SIT, together with the environmental benefits associated with not having to apply insecticides, has made it possible to use SIT for routine fruit fly control rather than only for full eradication. The feasibility of this approach has been confirmed by a number of cost–benefit analyses. The development of male-only strains has resulted in the organization of medfly SIT programmes in a number of countries of South and Central America, on the island of Madeira, and in Israel and Jordan, as well as pilot projects in South Africa and Australia and feasibility studies in some North African and European countries.

As the application of the SIT is based on the areawide concept, i.e. entire insect pest population management, molecular genetic tools are used for pest insect population analyses. This enables to measure the gene flow between neighbouring populations and to identify the natural local distribution limits of the target pest, as well as, most suitable sites for the erection of artificial barrier systems. Based on this information, Member States can be advised on the required extent of the pest insect control/eradication area and whether transboundary intervention measures are required, as is the case for the SIT operations against medflies in the Jordan rift valley.

6.1.1.2. Livestock Production

Radioactive and stable isotopes are widely used for quantifying and understanding the processes and interactions leading to the conversion of plants and other foodstuffs into animal products. Such knowledge can be used to understand and manipulate nutritional responses in ruminants. Studies have relied on volatile fatty acids labelled with carbon-14 to measure energy expenditure, and nitrogen-15, sulphur-35 and phosphorous-32 labels for measuring microbial protein synthesis. However, these techniques require surgical manipulation of the animal, with the attendant technical difficulties, and also raise issues of animal welfare. This has stimulated the development of simpler techniques, many of which are isotope based, to provide more workable approaches which can also be applied in developing countries.

In livestock reproduction, research is currently focused on two areas. The first is in understanding the mechanisms which control reproductive function at the cell and molecular levels using RIA and other techniques for measuring hormones and metabolites. The second deals with assisted reproductive techniques, which include in vitro fertilization, embryo construction from stem cells and the production of animals with genetically desirable characteristics.

In animal health there is continuing interest in understanding animal defence mechanisms using cell mediated immunity. Assays involving chromium-51 remain the basis of many such studies. A second area of interest is in antibody mediated immunological studies, where RIA and enzyme linked immunosorbent assay (ELISA) are essential tools. ELISA and RIA are also key components in animal disease diagnosis and in monitoring the effectiveness of control or eradication programmes that are based on conventional or recombinant DNA vaccines. The development of the polymerase chain reaction (PCR) technique allows rapid identification and characterization of genes, and gene amplification and manipulation. With the addition of radiolabelled markers such as microsatellites, this technique allows research into the genetic basis of resistance to disease and the genetic engineering of biologically active compounds.

By 1997, the application of SIT against tsetse flies had resulted in the eradication of this species on the island of Zanzibar and the elimination of trypanosomosis from livestock. A number of SIT pilot projects are being prepared in isolated areas of mainland Africa, notably in Ethiopia. The potential for successful integration of SIT with conventional methods against tsetse flies has been significantly advanced by recent improvements in mass rearing and aerial release techniques. In addition, SIT programmes to eradicate the new world screwworm from North and Central America have been implemented.

6.1.1.3. Food Safety

The safety and effectiveness of irradiation as a food treatment process is recognized internationally through the Codex General Standard for Irradiated Food, which was adopted by the FAO/WHO Codex Alimentarius Commission (CAC) in 1983. The CAC is now considering amending the present maximum permissible dose to allow irradiation of food produced under good manufacturing practices (GMP) with no restriction on dose absorbed.

The commercial application of food irradiation has increased significantly over the past five years and 34 countries are now using this technique for treating food products mainly for domestic markets. The global production of irradiated food has increased steadily to some 250 000 tonnes in 1999, of which approximately 80 000 tonnes are spices and vegetable seasonings originating mainly from developing countries.

More than forty countries have introduced national regulations or issued special permission to use the technique for treating one or more food items or classes of food. National regulations on food irradiation in Asia and the Pacific, Africa, Latin America and the Middle East are being harmonized with the Codex Standard and recommendations of the International Consultative Group on Food Irradiation (ICGFI) established under the aegis of the Agency, FAO and WHO.

The widespread and increasing incidence of foodborne illness caused by pathogenic bacteria and parasites and the consequent social and economic impact on the human population have brought food safety to the forefront of public health concerns. Although reliable statistics on foodborne diseases are available from a few countries, epidemics of foodborne pathogens such as *Escherichia coli* 0157:H7, *Listeria* monocytogenes and *Campylobacter* jejuni in Australia, Japan, Europe and USA have claimed thousands of victims and caused many deaths. In the USA alone, foodborne illnesses in 1998 were estimated to be about 76 million cases amounting to some 30% of the population with about 5000 deaths. Over the past five years research has focused on the effectiveness of irradiation as a sanitary treatment for foods of animal origin, fresh fruits and vegetables, and minimally processed foods. This has resulted in greater recognition of the value of the process in preventing outbreaks of food borne diseases by significantly reducing the level of contamination in foods by pathogenic microorganisms.

Small scale commercial application of irradiation has been carried out in several countries. This is expected to increase significantly in the USA following the regulatory approval of irradiation of red meat to eliminate pathogens. Up to one quarter of the annual production of about one million tonnes of ground beef is expected to be irradiated in the USA in 2000. Several large commercial X ray or electron beam irradiators are being built to meet this demand.

Irradiation is increasingly recognized as being effective in the phytosanitary treatment of food for insect control to replace fumigation with methyl bromide, a chemical that is being phased out globally for environmental reasons. The USA and ASEAN countries have taken the lead in introducing regulations to allow irradiation for this purpose and a commercial X ray irradiator in Hawaii, USA, is expected to be in operation by June 2000.

6.1.2. Future Trends

Nuclear based techniques are widely used for agronomic and related environmental research in essentially all developed and in an increasing number of developing countries. In many cases the isotopes themselves and long established equipment currently in use, such as neutron probes, liquid scintillation counters and optical emission spectrometers, have become more affordable and scientific personnel have been trained in their operation. However, it is expected that problems with the maintenance of equipment will persist in the majority of developing countries. The more precise isotope ratio mass spectrometers will continue to be increasingly used in developed countries owing to their technical advantages over emission spectrometers. There is also a general trend towards using variations in natural isotopic abundance. The implications of these developments for developing countries will be assessed during in an international symposium being convened by the Agency and FAO in late 2000.

6.1.2.1. Crops and Cropping Systems

The intensification of crop production to increase yields while minimizing environmental degradation and pollution will require an integrated approach to crop, soil and water management. Neutron probes, as well as non-nuclear techniques such as time domain reflectometry capacitance probes, will find more widespread use in providing critical information to support water conservation and management strategies in rain fed as well as irrigated agriculture.

The importance of controlling soil erosion, which is a major threat to global food security, will provide considerable scope for the wider use of caesium-137 and other fallout radionuclides to identify practical measures at both the farm and catchment levels.

There will be continued emphasis on using natural sources of nutrients such as rock phosphates, biological nitrogen fixation, crop residues and manure to supplement manufactured sources, particularly in least developed countries. This will result in continuing demand for existing tracer techniques based on nitrogen-15 and phosphorous-32. These techniques will help to identify efficient nutrient management practices tailored to local needs.

Plant genotypes with high yield potential and tolerance to soil and environmental stresses caused by salinity, acidity or drought will play an increasingly important role in many parts of the world. Tracer techniques such as carbon-13 could be more widely applied to assist in identifying germplasm that performs well under adverse conditions.

Future advances in crop improvement will also depend on understanding and manipulating crop genomes for producing desirable traits. Recent developments in molecular tools will be used increasingly to define the genetic components of crop productivity and stimulate novel approaches to plant breeding and crop improvement. Induced mutagenesis will continue to be important for extending the genetic diversity of food and industrial crops.

There is general acceptance of the need to develop and implement more environmentally sustainable methods to manage insect pests and to establish pest free areas for facilitating international trade in agricultural commodities and meeting international sanitary and phytosanitary standards. There is considerable potential for expanding current applications of SIT and in developing the technique further to facilitate its application against other major insect pests. The ability to manipulate the genome of insects using molecular biology and genetic engineering will facilitate these efforts through the development of improved insect strains.

At the same time, there are still no commercial enterprises selling sterile insects or services related to SIT. This technique involves high capital investment costs, is large scale and is logistically demanding. Nevertheless, the development of an SIT package for a specific key pest, involving mass rearing and aerial release systems, generally requires less funding than the development of a new synthetic insecticide. With more realistic accounting of the negative environmental effects of insecticide applications and as further improvements occur in the cost effectiveness of biologically based methods, the economic feasibility of SIT is likely to become increasingly apparent to governments and the scientific and development communities.

6.1.2.2. Livestock Production

In the short term, most developing countries will continue using current proven techniques for improving breeding management, disease control and nutrition to increase productivity in their farming systems. However, population and income growth coupled with urbanization is rapidly increasing the demand for food in developing countries and livestock farming is undergoing radical changes. As these farming systems become more commercially oriented and intensive, they will look to more advanced techniques now being developed as tools for further improvement of productivity.

The long term future for increasing livestock productivity lies in manipulation at the molecular and genetic levels. Two key areas seem to offer the most potential. The first is the identification, characterization and utilization of genes that control productivity and resistance to disease and the environment. Radiolabelled genetic microsatellites and the PCR technique will be central to this approach. The second important area is genetic and synthetic engineering of biologically active proteins, which encompasses the engineering of vaccines, therapeutic agents and diagnostic reagents. In almost all cases, isotopes will be used as markers for the characterization of the protein and the protein constructs, as well as to track and study them.

6.1.2.3. Food Safety

Through the work of ICGFI, the dissemination of factual and objective public information material, and the conduct of well designed research and market trials on irradiated food, the potential applications and benefits of food irradiation have widened and much of the earlier opposition by major consumer associations has been significantly reduced. The food industry in general has a better understanding of the benefits of this process and is increasingly prepared to market irradiated food. Therefore it is expected that there will be more widespread application of this technique in the years ahead.

Screening methods for residues in food products arising from the use of pesticides and veterinary drugs in intensive agriculture, will increasingly involve ELISA and RIA to allow cost effective and reliable wider scale assurance of food quality and safety.

6.2. IMPROVING HUMAN HEALTH

6.2.1. Current Status and Achievements

6.2.1.1. Prevention

Childhood malnutrition and micronutrient deficiencies remain serious global problems. In this context, isotopic tracer techniques have been developed for measuring whole body vitamin A under conditions of supplementation, which have now been applied in food fortification and dietary improvement programmes in several Member States to address problems of vitamin A malnutrition in children and pregnant or lactating women. Similarly, the assessment of iron absorption from diets to evaluate its bioavailability is an important nutritional measurement. Nuclear techniques based on stable isotopes are uniquely suited for targeting and tracking progress in food and nutrition development programmes. These techniques are used for measuring the uptake and bioavailability of many important vitamins and nutrients.

Osteoporosis, cardiovascular diseases, AIDS, protein energy malnutrition, genetic disorders, diabetes and obesity are all accompanied by abnormalities in body composition. The monitoring of body composition can provide the basis for initiating preventive intervention measures. A technique based on isotope dilution using deuterium or oxygen-18 is gaining wider acceptance since it is inexpensive, accurate and can be applied under field conditions. X ray absorptiometry for bone density measurements is another important nuclear technique that is widely used in the study of osteoporosis.

6.2.1.2. Diagnosis

Nuclear medicine is a clinical speciality primarily devoted to diagnostic and research applications of internally administered open sources of radioactivity. It has been widely applied because of its non-invasive nature, and its ability to provide information about organ function and detect abnormalities at a very early stage. Today, nuclear medicine techniques are used in a broad range of medical specialities, such as oncology, endocrinology, cardiology, neurology and nephrology. There are nearly one hundred different, standardized nuclear medicine diagnostic and therapeutic techniques available for the study of the major organ systems.

Tables 3 and 4 show the extent to which gamma camera techniques have been applied in industrialized countries compared with developing countries and countries with economies in transition.

TABLE 3. Gamma cameras installed in industrialized countries

Industrialized countries	**Number of gamma cameras**	**Gamma cameras per million inhabitants**
North America	8944	33.0
Japan	2700	21.6
Australia	300	16.8
West Europe	3740	10.3
TOTAL	15 684	20.2

TABLE 4. Gamma cameras installed in developing countries and countries with economies in transition

Developing countries and countries with economies in transition	**Number of gamma cameras**	**Gamma cameras per million inhabitants**
Eastern Europe	1165	3.0
Latin America	953	2.1
West Asia	166	1.0
Asia	879	0.3
Africa	86	0.2
TOTAL	3249	0.75

Radioimmunoassay is an established and mature in vitro diagnostic nuclear technique used to detect and quantify drugs, metabolites, hormones, enzymes, cancer markers and viral antigens for early clinical laboratory diagnosis.

Molecular nuclear diagnostic techniques have been increasingly adopted for the diagnosis and monitoring of diseases. The PCR technique is one of the most commonly applied molecular methods for both basic research and clinical diagnosis. It is particularly useful when only traces of starting DNA material are available for analysis. Various PCR techniques are being used for the diagnosis and monitoring of Chagas disease, leishmaniosis, hepatitis B and C, cervical cancer and leukemia. They are also used for direct detection of mutations responsible for drug resistance in malaria and tuberculosis and for the diagnosis of genetic defects such as thalassemia and muscular dystrophy.

Helicobacter pylori is a chronic bacterial infection affecting a large segment of the world's population leading to chronic gastritis, peptic ulcers and also cancer. A large proportion of young children in developing countries suffer from this infection, making them susceptible to diarrhoeal diseases. A simple breath test using substrates enriched with carbon-13 or carbon-14 and measurement of labelled CO_2 has been recognized as the best and most cost effective means of diagnosis of this infection.

6.2.1.3. Treatment

Teletherapy is the most common radiation therapy technique, where the radiation source is placed at a distance from the patient. Teletherapy has evolved from the use of X ray tubes to machines where gamma radiation is derived from cobalt-60 sources. Over the last thirty years, teletherapy in the industrialized countries has tended towards the use of linear accelerators producing electrons and high energy X rays up to 25 MeV, more penetrating and with very sharp beam edges, capable of reaching deep seated tumours with improved accuracy. About 2000 cobalt machines and 6000 accelerators are in use worldwide.

Brachytherapy, the insertion of radioactive sources into cavities adjacent to tumours or even invasively directly into tumours, has also advanced rapidly. Radium-226 has almost completely been replaced by caesium-137 and increasingly by new micro high dose rate iridium-192 sources of high specific activity that are under 1 mm in diameter. These small sources have reduced treatment times typically to between ten and twenty minutes instead of between two and five days. Procedures for insertion are easier and new sites are accessible. These sources can be directed into the small bronchi of the lungs, bile ducts and small heart vessels whereas the older brachytherapy units are almost exclusively confined to the treatment of the uterine cervix. The Agency has issued recommendations on the appropriate techniques for calibrating these sources.

The Directory of Radiotherapy Centres (DIRAC) is a computerized database containing detailed information on therapy institutions worldwide, their teletherapy and brachytherapy machines, dosimetry equipment and treatment planning as well as staff strength at the institutions. The operation of DIRAC has been shared with WHO since 1998. Table 5 shows information on teletherapy machines by region. The difference in the number of machines per million population illustrates the vast discrepancy in equipment and hence the availability of treatment in the different regions. About four megavoltage machines per million of the population is an acceptable norm for developed countries. In developing countries, the resources are insufficient to provide a comprehensive service. The linear accelerator is clearly the preferred technique in North America and Australia, where it comprises over 90% of all teletherapy machines, and also in Europe where its share is 75%. In contrast, medical accelerators comprise just 20% or less of teletherapy machines in the developing parts of the world.

Brachytherapy is entering the field of management of ‘benign’ diseases with endovascular treatment, the insertion of small sealed radioactive sources into blood vessels. This is used in the prevention of coronary artery restenosis after bypass surgery or dilatation of constricted arteries, in particular heart vessels. The results now becoming available indicate that the significant restenosis rate may have dropped by a factor of four for different surgical interventions.

Radionuclide targeted therapy is growing in its range of applications and clinical efficacy. The successful treatment of neural crest and neuroendocrine tumours and non-Hodgkin’s lymphoma, as well as effective palliation of the pain of bone metastases, are current developments.

The challenge for the next decade will be to raise the standards in developing countries to levels where the best modern techniques can safely be incorporated into treatment practices. This will also involve the introduction of multidisciplinary clinics for decision making on patient management.

TABLE 5. Number of centres and teletherapy machines by region

Region	Population 1998 (millions)	Radio-therapy centres	Cobalt-60 units	Clinical accelerators	Teletherapy machines (total)	Machines per million population
North America	300.9	1903	207	2251	2458	8.2
Central America	134.1	139	115	30	145	1.1
Tropical South America	276.2	266	219	122	341	1.2
Temperate South America	54.3	139	128	46	174	3.2
Caribbean	29.4	18	23	1	24	0.8
Western Europe	387	1027	410	1109	1519	3.9
Eastern Europe	390.6	334	508	182	690	1.8
Northern Africa	138.2	59	54	41	95	0.7
Central Africa	358.6	22	25	2	27	0.1
Southern Africa	56.5	21	19	27	46	0.8
Middle East	221.3	91	64	56	120	0.5
South Asia	1245.1	221	286	46	332	0.3
South East Asia	477.2	81	71	59	130	0.3
East Asia	1430.9	1107	606	948	1554	1.1
Australia & Pacific Islands	22.6	49	5	113	118	5.2

6.2.1.4. Metrology and Quality Assurance

Agency Codes of Practice for the determination of absorbed dose in the calibration of a radiotherapy beam were published some 30 years ago, when the status of radiotherapy in developing countries was based mainly on conventional X rays. *Absorbed Dose Determination in Photon and Electron Beams: An International Code of Practice*, published in 1987, is probably the standard for radiotherapy dosimetry most used in the world. It provides internationally accepted, harmonized procedures for radiotherapy beam calibration. A new Code of Practice, *The Use of Plane-Parallel Ionization Chambers in High-Energy Electron and Photon Beams*, was published in 1997 to update the earlier code and complement it with respect to plane-parallel ionization chambers.

The Agency has played an important role in this area for many years by maintaining a network of Secondary Standards Dosimetry Laboratories (SSDLs), which provide traceable calibration services for radiotherapy, diagnostic radiology and radiation protection, and dose quality audits to SSDLs and hospitals. The IAEA/ WHO SSDL network includes 75 members in 58 countries, and is supported by 15 Primary Standards Dosimetry Laboratories (PSDLs) and five international bodies and committees. Recently, more effort has been directed to the dissemination of standards for diagnostic radiology X rays, particularly in mammography.

For more than thirty years, the Agency and WHO have operated a service to validate the calibration of radiation beams in developing Member States using thermoluminescent dosimeters that are sent and returned by post. It has been the model followed by other countries and regions in developing their own services. During the last three years, the percentage of deviations within acceptance limits has increased from approximately 60% to 84% in 1998; all results outside the acceptance limits have been followed-up. Dosimetry practices in many hospitals in developing countries still need to be strengthened in order to attain levels of hospitals that perform modern radiotherapy in industrialized countries.

6.2.2. Future Trends

6.2.2.1. Prevention

Isotopic techniques have just begun to be applied in developing countries where they not only have the potential to benefit millions through improved nutrition and nutrition monitoring techniques, but also serve as specific indicators of broader social and economic advances. In the use of these techniques, greater attention is being given to the monitoring of the health status of elderly people, women and children, and to applications, including preventive measures, involving the monitoring of nutritional status (particularly obesity).

6.2.2.2. Diagnosis

Expanded use of PET is forecast. Its advantages include more accurate imaging and the ability to provide information about metabolic function, which is not possible using alternative medical imaging techniques. Its use can improve the management of a significant number of diseases, including cancer, neurological disorders and coronary artery disease. There are currently about 150 centres for PET around the world operating a total of about 200 cameras located mainly in developed countries.

Molecular techniques are expected to have further applications, such as predictive markers for malignant and degenerative disorders, for drug design and gene therapy, and also for the detection of minimal residual disease and of new diseases. The trend in the techniques will be quantitative, multiplex, in situ PCR and multiplex DNA sequencing, using enriched stable isotope labels.

Metabolic and receptor imaging techniques are now available in diagnostic nuclear medicine for the study of tissue viability, especially in the field of oncology (tumour viability) and cardiology (myocardial viability). Gamma probes for sentinel lymph node detection and radioguided surgery are expected to play an important role in decision making in surgical oncology.

6.2.2.3. Therapy

Increasingly in developed countries, conformal radiotherapy is being used to increase the dose delivered to tumours. Another development is the use of protons and heavy ions as a means of delivery of radiation. Proton therapy has been used in over 25 000 patients, while heavy ions have been used in 1000. These particle techniques will need to demonstrate significant benefits to justify their considerably higher costs before becoming generally available.

There is a significant role for both radiosurgery and microsource brachytherapy in the treatment of smaller benign conditions. Intravascular radionuclide therapy for the prevention of restenosis following angioplasty in coronary artery disease is expected to expand using beta and gamma emitters as more clinical results become available.

Developing countries over the last decade have shown a threefold increase in the amount of equipment available for use. This trend is likely to continue, especially for countries with an increasing demand for comprehensive health services. While the replacement of cobalt-60 by linear accelerators is likely to continue in developed countries, the trend in developing counties is not so clear. The Agency will continue to assist developing countries to strengthen their radiotherapy services through co-ordinated research and technical co-operation.

6.2.2.4. Metrology and Quality Assurance

A new international Code of Practice is being published this year on behalf of the Agency, WHO, PAHO and ESTRO for radiotherapy dosimetry based on the new standards of absorbed dose to water. It covers the entire range of beam modalities used in radiotherapy, from conventional X rays to protons and heavy ions, providing a harmonized standard for the dosimetry of all types of radiotherapy beams. The new Code reduces the uncertainty in the determination of absorbed dose in reference conditions (beam calibration), is based on a more robust system of primary standards, and has a simple formalism. Several projects are being conducted for SSDL members to implement the Code rapidly so that they can disseminate the new standards to radiotherapy users in their respective countries.

6.3. MANAGING WATER RESOURCES

6.3.1. Current Status and Achievements

Less than 2.5% of the total amount of water on Earth is available as fresh water. Of this quantity, only 0.28% is accessible for use by people from rivers, lakes and groundwater sources. The balance of this fresh water is unavailable since it is in the form of ice, soil moisture or is only found very deep underground. Nuclear techniques, using the abundance of naturally occurring environmental isotopes, can provide unique information that assists in characterizing hydrological systems. These techniques are being used globally for resolving a broad spectrum of problems encountered in water resources assessment and the sustainable development and management of freshwater resources. The technological and economic benefits of isotopic applications in hydrology have been demonstrated in several areas, particularly when these applications are an integral part of hydrological practices in the water sector.

Isotope hydrology is based upon the use of a variety of naturally occurring stable and radioactive isotopes. Applications of some artificially produced radioactive tracers have also gained prominence in recent years. The abundance of these isotopes in the hydrological cycle can be measured using a variety of analytical methods, including isotope ratio mass spectrometry (IRMS), accelerator mass spectrometry (AMS) and a range of particle counting techniques. In almost all current applications of isotope hydrology, interpretation of the hydrological process of interest is based upon naturally occurring levels of these isotopes. In some cases, the artificially enriched abundance of a particular isotope may be used as a tracer that is introduced into a particular system.

It is estimated that there are now over 100 practising isotope hydrology laboratories around the world capable of applying at least some of these isotopes to water resources investigations. A significant achievement in recent years has been the increasing uptake and integration of isotope hydrological techniques into the broader field of water resource investigations. The increasing recognition that these techniques have an integral role to play in water resources assessments has been made possible by, for example, recent developments in IRMS instrumentation that have resulted in greater precision and reliability becoming routinely attainable by laboratories. In addition, increased sample throughput has been made possible by new, automated sample processing techniques, while at the same time a reduction in sample size and pre-processing requirements is making the techniques more widely accessible to non-specialists. These technical advances are being complemented by the development of new software tools that assist in the analysis of isotope hydrological data. These tools allow the testing and assessment of possible interpretations of field data.

The Agency has managed a Global Network of Isotopes in Precipitation (GNIP) database in co-operation with the World Meteorological Organization for more than three decades. This network provides the basic data that are an essential pre-requisite for the application of isotopic techniques in water resources assessment and management.

The sustainability of groundwater supplies from aquifers in arid regions of Africa and the Middle East have been assessed by using the stable and radioactive isotopes of oxygen, hydrogen and carbon. For example, adjacent to the Nile River in Egypt and Sudan, fresh water originating from the infiltration of river water was distinguished from pre-existing groundwater that was a non-renewable resource. This helped design adequate management strategies for local water supply systems. The hydrological boundaries of major aquifer systems, as well as aquifers with non-renewable groundwater in the Middle East region, have been mapped using isotope techniques. Groundwater resources in most developed countries are commonly assessed using similar isotope methods.

A detailed study has been used to estimate the age of water in Lake Baikal, the deepest and largest lake by volume on Earth that holds one fifth of global freshwater resources. The study has indicated that the system is highly vulnerable to short term pollution and this has immediate implications for the management and control of surface waters entering the lake.

6.3.2. Future Trends

The range of well established and field verified isotope techniques and their applications to water resources management are now being complemented by the application of isotopes such as chlorine-36 and carbon-14 on extremely small sample sizes by AMS. The use of chlorine-36 has become possible as a result of technology spin-offs from developments in particle accelerator techniques, and recognition they can be applied to environmental and hydrological studies.

Other new techniques, such as atom trap trace analysis (ATTA), are emerging where trapping, detection and counting of single atoms is possible. Isotopes such as krypton-81 and krypton-85 with extremely low natural abundances are detectable by ATTA. Prior to these developments, measurement of these isotopes required prohibitively large water samples. These technical breakthroughs open up new possibilities for these isotopes, and for others such as caesium-135 and caesium-137, that may be applied to groundwater, atmosphere and marine transport processes and for dating extremely old ice and groundwater samples.

Easier access to new analytical techniques and instrumentation will result in a wider use of isotope techniques in hydrology. In addition, emerging analytical techniques, such as laser assisted isotope ratio measurements, could make isotope analysis comparable in cost to routine chemical analysis.

Current research is expected to lead to a clearer understanding of how naturally occurring isotopes behave in environmentally complex systems. These include a better understanding of the behaviour of stable isotopes of water during atmospheric evaporation–condensation, evaporation–transpiration in plant water use, identification of water sources used by plants, interactions between soil gases and groundwater, and isotopic fractionation accompanying biological transformations in plant and soil bacterial processes.

6.4. PROTECTING THE ENVIRONMENT

6.4.1. Current Status and Achievements

Nuclear techniques can detect and measure radioactive nuclides and other non-radioactive sources of pollution such as heavy metals and other trace elements in air, surface and groundwater, soil, and the marine environment. A second class of techniques based on isotopic measurements, either natural, anthropogenic or introduced artificially as tracers, can provide detailed information about complex ecological systems and the processes which control the fate of pollutants in the environment.

6.4.1.1. The Atmosphere and Climate Change

Fine airborne particulate matter (APM) originates mainly from anthropogenic activities such as industrial and residential combustion and vehicle emissions. Studies show that the most harmful health effects are due to fine particles smaller than 2.5 μm in diameter. This is because they not only enter the trachea and primary bronchi in the lungs, but can also penetrate to the alveoli. In response, some countries have recently strengthened air quality standards relating to fine particles. Ongoing research is focused on obtaining comparative data on levels of fine APM in the air, identification of the main sources of this pollution, and obtaining information on the long range transport of air pollution.

Certain biological organisms integrate airborne pollutants over time. An approach known as biomonitoring measures the changes in appropriately selected plants to evaluate the kind of pollution, its source and intensity. Biomonitoring is particularly useful when many measurements at different locations are needed; it reduces the need for continuous chemical monitoring and offers the potential of retrospective monitoring. Nuclear analytical techniques have proven to be an effective analytical tool in such studies.

The electron beam accelerator technique to remove SO_2 and NO_x, the most harmful pollutants, from the exhaust gases of thermal power plants has matured to the point that large scale, successful demonstrations have been held. A plant using electron beam irradiation to treat flue gas from a coal fired plant in Chengdu, China, has been in operation since September 1997. The plant achieved its design performance with satisfactory recovery of fertilizer for agricultural use. A second plant designed to treat gas started operation in Japan in 1999. A third demonstration project in Poland to treat flue gas from coal fired boilers is expected to begin operation by June 2000.

Stable and radioactive isotopes of carbon provide a unique tool for investigating the causes of global warming. This aspect of the use of isotopes has gained greater importance during the last four years as a result of the Kyoto Protocol covering greenhouse gas emissions. Isotopic techniques have been used to monitor the impact of El Niño events on surface precipitation and deposition of atmospheric pollutants such as nitrogen and sulphur.

Isotopic techniques also provide a record of past environmental conditions such as temperature, humidity and where water sources originated. These can then be compared to present-day environmental conditions in order to detect climatic change. Noble gases such as neon and radiogenic helium and carbon-14 in groundwater aquifers in parts of southern USA, Mexico, South America, and southern Africa have been used to estimate the cooler climatic conditions (about 5 ^{o}C lower) of recharge thousands of years ago.

6.4.1.2. The Marine and Terrestrial Environment

Nuclear techniques, being extremely sensitive and isotope specific, can dramatically complement non-nuclear methodologies for assessing pollution and particular understanding oceanographic processes. They can be applied to assess the environmental distributions of both radioactive and non-radioactive contaminants. Isotopic measurements using natural, anthropogenic or artificially introduced tracers can provide detailed information about complex ecosystems and the mechanisms that control the fate of diverse pollutants in the environment. In particular, isotope ratio techniques can frequently provide a unique fingerprint to facilitate source apportionment assessments, and differential decay rates can provide an insight into the time scales of oceanographic processes.

There has been much work carried out to understand the distribution, behaviour and transport of radionuclides in the environment. The fate of radionuclides must be understood in order to assess possible environmental or human health consequences from unplanned releases. Extensive studies have been undertaken to investigate the worldwide distribution of radionuclides from global fallout and to study the impact of reprocessing facilities, nuclear weapon test sites, radioactive waste dumping sites and nuclear accidents, including the Chernobyl accident. Global fallout from atmospheric nuclear weapon tests is, with few exceptions, the main source of anthropogenic radionuclides in the world's oceans. In some areas, however, such as the Irish and North Seas, authorized releases of radionuclides from reprocessing plants have exceeded the concentrations from global fallout. The Baltic and Black Seas have been the main marine reservoirs of radionuclides released after the Chernobyl accident. The Baltic Sea still has the highest marine concentration of caesium-137, about 100 Bq/m^3, in the world.

Human exposure to marine radioactivity has been assessed. One study, published and reviewed internationally in 1997, co-ordinated by the Agency's Marine Environment Laboratory in

Monaco, compared concentrations of anthropogenic caesium-137 and natural polonium-210 in sea water and biota, and estimated radiation doses delivered to the human population through consumption of seafood. Comparing different oceanic regions, the dominant contribution to the collective dose was consistently from natural polonium-210, which in some areas was two orders of magnitude higher than that from caesium-137. However, in all cases the doses were well below the accepted value for the public of 1 mSv.

Isotope techniques have been used to determine the causes of the rising water level of the Caspian Sea. Results indicate that the responsible mechanism is increased river discharge, due primarily to changes in the hydroclimatic conditions in the catchment area. Similarly, measurements of radium-226 and radon-222 have been used recently to identify a large, but previously unrecognized, submarine discharge of fresh groundwater into the oceans, resulting in better understanding and management of both the marine environment and coastal aquifers. Finally, sources of terrestrial environmental contamination from nuclear testing in French Polynesia, Kazakhstan, the Marshall Islands and the Sahara Desert have also been assessed, or re-assessed, through international co-ordinated studies.

6.4.2. Future Trends

6.4.2.1. The Atmosphere and Climate Change

Research is increasingly being focused on fine APM. Although it is known that these particles are contributors to ill health, it is still uncertain which chemical elements or compounds within the particles are responsible for the most harmful effects. Future effort is expected on studies of various chemical compounds in connection with pulmonary diseases. Extensive databases on toxic elements will be combined with epidemiological and other health related studies to establish a correlation between the incidence of diseases such as lung cancer and atmospheric pollution.

6.4.2.2. The Marine and Terrestrial Environment

Future applications of nuclear techniques in the marine and terrestorial environment will allow improved assessment of the distribution and fate of both radioactive and non-radioactive contaminants. New monitoring systems will rely on in situ marine radioactivity monitors with satellite data transmission and the use of sea bed gamma spectrometry for mapping the radioactivity of sediments. Novel isotopic techniques are being developed to study oceanographic processes, climate and contamination of the marine environment. Improved marine information systems on contamination of the marine environment and oceanographic parameters, together with enhanced computer models, will provide better predictions for the dispersion of radionuclides and other contaminants from their sources of origin located inland, in coastal areas or in the open ocean.

In the case of the terrestrial environment, the major trend will be dictated by the increased requests to evaluate (or re-evaluate) by internationally validated measurements the residual radioactivity (source term) at sites which were intentionally or accidentally contaminated during the Cold War. More emphasis will be put on the structural, morphological and chemical characterization of hot particles. There will also be an increased need to evaluate through similar international approaches radioactive contamination (source term) at uranium mines.

6.5. INDUSTRIAL APPLICATIONS

6.5.1. Current Status and Achievements

Techniques based on radioisotopes and radiation find widespread application in industry to improve the performance and efficiency of processes, the quality and the safety of industrial products. They may also confer both direct and indirect environmental benefits as compared with alternative techniques.

Gamma irradiator facilities as well as electron beam accelerators are used for a number of radiation processing and irradiation applications, including, curing of plastics and rubber, waste management and radiation sterilization. Radiation processing has also produced novel new materials such as hydrogel dressings, for the treatment of wounds. Radiation sterilization of tissues, pharmaceuticals and pharmaceutical raw materials is growing steadily. In developed countries almost half of disposable medical products are sterilized using radiation. This might well increase to up to 80% with the phasing out of ozone depleting and hazardous chemical alternatives.

A large number of radioisotopes in various chemical and physical forms are used as tracers in industrial research and development activities to check equipment performance, optimize processes, calibrate models or test installations. Gamma and neutron scanning techniques for the inspection of columns, pipes and tanks and nucleonic gauges are used for on-line measurement and process control.

X ray and gamma radiography and their complementary non-destructive testing methods are extensively used to detect defects in industrial equipment and products.

6.5.2. Future Trends

The use of radiation techniques for material modification is expected to grow, particularly electron beam techniques. The petroleum, petrochemical as well as mineral processing industries are expected to see an increased application of radiotracer and sealed sources technique.

Non-destructive testing is likely to make greater use of digital and computer based applications, the main focus being to improve both the efficiency and reliability of inspection. Efforts now under way will harmonize, the training and certification of personnel worldwide. New developments employing micro-focus X rays are expected to provide greater reliability and sensitivity with reduced operator dependence.