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# Nuclear power: An overview in the context of alleviating greenhouse gas emissions

*Supporting document to the Second Assessment Report of the Intergovernmental Panel on Climate Change prepared by the International Atomic Energy Agency and the OECD Nuclear Energy Agency*

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## FOREWORD

One of the functions of the IAEA is to provide comprehensive information on nuclear power development and technologies in order to accelerate and enlarge the use of atomic energy for peaceful purposes. In this connection, and in particular in response to the recommendations of the Agenda 21 adopted by the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro (Brazil) in June 1992, the IAEA has been contributing to the work of the Intergovernmental Panel on Climate Change (IPCC).

The IAEA has been responsible jointly with the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) for preparing the nuclear power sections of the Second Assessment Report (SAR) of IPCC.

The present publication has been prepared as a background paper for the SAR, with the objective of providing more detailed and extensive information on the potential role of nuclear power in alleviating the risk for global climate change.

Most of the information and data given in this publication are based upon IAEA and OECD/NEA working papers and publications, which in turn are reflecting state-of-the-art scientific and technical knowledge of senior experts from their Member States and consensus views from these experts.

The IAEA is grateful to the "Lead Authors" of the IPCC/SAR chapter on "Energy Supply", and in particular to the Convening Lead Authors for this chapter, for their challenging comments and remarks on the nuclear section during the preparation of the SAR. The Scientific Secretaries for this publication were E. Bertel of the IAEA and P. Girouard and G.H. Stevens of the OECD/NEA.

## *EDITORIAL NOTE*

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# 1. INTRODUCTION

The present publication gives a brief overview of the current development of nuclear power worldwide, covering essentially technical, economic and environmental aspects. Policy issues related to implementation instruments and potential barriers to nuclear power deployment are also touched upon. Views are given on the possible medium and long term development of nuclear power, as a means for alleviating greenhouse gas emissions from the electricity sector. Advanced technologies for the reactors and their associated fuel cycles are described, including advanced fission reactors and fusion energy. Direct costs and externalities are given for the present generation of nuclear power plants as well as for power plants to be commissioned in the coming decades. Environmental burdens and risks are analysed with emphasis on potential risks of accident, radioactive waste, and atmospheric emissions in routine operation, focusing on greenhouse gases.

# 2. STATUS AND TRENDS

The use of nuclear power for electricity production dates back to the late 1950s. Nuclear power is a proven technology that is already contributing significantly to electricity supply worldwide with some 17% of the total generation [1]. At the end of 1993, there were some 430 nuclear power reactors connected to the electricity supply networks in 30 countries, with a total installed capacity of some 338 GW(e) which generated nearly 2100 TW·h in 1993. In some 15 countries, nuclear power plays a major role in the electricity system, providing one third or more of the total supply. In OECD countries, electricity generation from nuclear power totalled some 1700 TW·h in 1993 and provided some 23% of the electricity consumed in the area [2]. In the world, the accumulated operating experience of nuclear power plants exceeds 6900 reactor-years. The operating performance has improved substantially over the last decade and the average energy availability factor of the nuclear power plants in operation has been close to or higher than 70% since 1984 [3].

Nuclear power programmes have slowed down in many countries in recent years, owing to lower than expected growth rate of electricity consumption in industrialised countries, lack of funding availability in developing countries, and also owing to public concerns regarding nuclear safety and radioactive waste disposal. In 1993, eight new nuclear power plants were connected to the electrical grid in six countries and, at the end of the year, there were 55 nuclear power units under construction in the world with a total capacity of some 44 GW(e). By the turn of the century, the installed nuclear capacity in the world will reach some 370 to 380 GW(e), depending on construction and licensing lead times of the plants being built. Most of the additional nuclear capacity will be brought into operation in Asia and in eastern and central Europe. In western Europe and North America, there will be few new base load electricity generation plants commissioned since the demand for electricity is not growing significantly. In the other regions of the world, nuclear power will remain a relatively small contributor to electricity supply in the short term.

A broad range of factors will influence nuclear prospects in the medium and long term. However, up to 2015, rapid changes in electricity supply strategies are unlikely to occur owing to the relatively long lead times prevailing in the electricity sector. Therefore, projections can be derived from a bottom-up approach based upon a review of nuclear programmes and plans in the different countries of the world. The estimates given in Table I are the result of a review carried out yearly by IAEA and NEA with the assistance of a group of international experts, in order to develop plausible medium term scenarios for nuclear electricity generation [4]. The low and high cases presented in Table I reflect contrasting but not extreme assumptions on the parameters which may influence the actual realisation of national nuclear power development programmes and plans. The low case corresponds to a continuation of the present stagnation owing to public opposition and slowly increasing electricity demand in OECD countries, institutional and socio-political uncertainties in eastern and central Europe, and lack of funding ability in developing countries. In that case, the nuclear power plants under construction will be completed but only those countries where nuclear programmes are already firmly committed, e.g., China, France, Japan and the Republic of Korea, will order and commission new units. The high case reflects a moderate revival of nuclear power development that could occur in light of a more comprehensive assessment of the macroeconomic and environmental aspects, including greenhouse gas emissions, of the different options available for electricity generation. This revival would occur mainly in western Europe and to a lesser extent in North America. In eastern and central Europe, nuclear power programmes will be implemented according to the present plans with the construction of advanced reactors with enhanced safety features. In Asia, nuclear power will be developed in line with the expected rapid growth of electricity demand and the competitiveness of nuclear power in many countries of this region.

TABLE I. PROJECTIONS OF NUCLEAR GENERATED ELECTRICITY (TW·h)

| REGION | 1993 | 2000 | 2010 | 2015 |
|---|---|---|---|---|
| North America | 699 | 695<br>714 | 660<br>668 | 672<br>703 |
| Latin America | 11 | 32<br>34 | 29<br>54 | 34<br>62 |
| Western Europe | 772 | 779<br>786 | 765<br>917 | 688<br>994 |
| Eastern Europe | 262 | 336<br>387 | 405<br>557 | 363<br>643 |
| Africa | 7 | 10<br>11 | 11<br>29 | 6<br>35 |
| Middle East & South Asia | 6 | 20<br>20 | 26<br>47 | 37<br>58 |
| South East Asia & the Pacific | 0 | 0<br>0 | 0<br>15 | 0<br>42 |
| Far East | 337 | 456<br>467 | 634<br>742 | 697<br>884 |
| TOTAL | 2094 | 2238<br>2419 | 2530<br>3028 | 2497<br>3422 |

Note: the table gives rounded figures; for 2000 to 2015 the top line corresponds to the low case and the bottom line to the high case.

One of the major determinants in the development of nuclear power has been its competitiveness for base load electricity generation. Results from recent studies on the cost of nuclear generated electricity, present and projected, which are given in Section 8.1, show that nuclear power is among the cheapest options for base load electricity generation and will remain competitive in many countries during the coming decades.

## 3. POTENTIAL MARKETS

To date nuclear power has been used predominantly for electricity generation although some use is made of waste heat for process and district heating. Therefore, the development of nuclear power, as well as of other type of electricity generating plants, has been largely affected during the last years by the slowing down of electricity demand growth in OECD countries. In the long term, although this trend is expected to continue in industrialised countries, additional capacity will be needed in developing countries due to population growth, even taking into account efficiency improvements and policy measures for energy saving. The use of fossil fuels for electricity generation is likely to be limited by resource availability and, moreover, by the need to alleviate emissions of atmospheric pollutants, especially greenhouse gases. Market forces will drive the penetration of technologies which are non-greenhouse gas emitters since their competitiveness will be enhanced by standards and regulations to be adopted for limiting emissions. Furthermore, policy measures aiming towards sustainable development will provide additional incentives for the deployment of clean technologies and greenhouse gas free generation options. Therefore, nuclear power, together with renewable sources, is likely to become more attractive.

Several national studies have looked in detail at the actual and potential impacts, especially on the risks for global climate change, of substituting nuclear power or other generation technologies for fossil fuels, particularly coal [5–13]. The share of nuclear power in total electricity generation, which is already exceeding 70% in some countries such as France, can be increased in most countries, taking into account the technical feasibility of operating nuclear power plants in a load-following mode. Advanced reactor designs, fuel management and material choices could offer enhanced capabilities in this regard. However, high capital intensive nuclear power plants are likely to remain in operation mainly for base load generation for economic reasons.

On the other hand, technological progress, including the development of small and medium size reactors (SMRs), i.e., reactors having a capacity smaller than 600 MW(e), will allow non electrical uses of nuclear power such as heat supply, marine propulsion and potable water production. The development of economically competitive electricity driven road vehicles could have a major impact on land transport and provide additional market for base load electricity generation. Should hydrogen become a widely used energy vector, it might be envisaged that nuclear electricity could be used to produce hydrogen for fuelling peak-load plants, as well as for fuel-cells and other transportable energy converters, thus enhancing the penetration of nuclear power into the energy supply market.

Nuclear reactors could be used as direct heat sources for a wide variety of industrial, commercial and residential uses. Many of these heat loads are less than 200 MW(th) so will require full development of SMRs and, for some applications, the development of further heat transfer technologies. A number of industries including food processing, paper and textiles could be serviced by water cooled reactors. Others, including non-ferrous metals, heavy oil production, petrochemicals, coal gasification, would need the higher temperatures available from high temperature gas cooled reactors (HTGCRs).

There is extensive scope in the district and industrial heat supply sectors [14] where there has been little penetration of nuclear power to date. However, the economics of transporting heat over long distances is questionable and current public attitudes towards nuclear power could prove to be a major obstacle to the implementation of nuclear power plants for heat supply if the plants have to be sited close to centres of high population. While large size reactors would not be acceptable, the development of SMRs could facilitate the penetration of nuclear power in these sectors. Given sufficient incentives the necessary development of reactor types adapted to heat supply could well be carried out in the coming decade and they could be available for commercial deployment early in the next century. At that time there could be several hundred sites worldwide where reactors in the range 150–250 MW(e) could be built, the number of opportunities increasing thereafter in line with growth in heat demand.

District heat markets are currently restricted to specific countries that are generally in the north, such as Finland, Germany, Russia and Switzerland, where there are heat distribution networks already in existence. The obvious immediate market for SMRs is the replacement of existing fossil-fuelled plants. In some of these countries many of the plants have been recently refurbished or renewed, thus limiting the short-term scope for SMRs. Further expansion may require a concerted effort to install integrated regional distribution networks, within Europe for example.

Process heat markets lie mainly with large industrial complexes, where the demands justify the implementation of heat supply systems. In many cases, the economics favour cogeneration systems providing heat and power rather than dedicated electricity or heat generating plants. Small reactors have a definite advantage over large size reactors in this sector where multiple units would be necessary to guarantee the high degree of security of supply required by industrial users. The main competitors for SMRs on this market are fossil fuelled power plants. At the current low investment costs of fossil fuelled power plants, especially natural gas fired units, it is questionable if SMRs could compete at least in the short term. However, fossil fuel prices can be expected to increase as demand grows, and continuing development should bring reductions in SMR investment costs, providing market incentives for the deployment of nuclear power for heat supply probably after 2015.

A recent IAEA study [15] suggests a demand for potable water requiring additional sea water desalination capacities of some 12 million $m^3$/day in the Mediterranean area and the Middle East by 2000. The same study indicates that SMRs, deployed at commercial rate would become economically competitive with fossil fuelled plants for sea water desalination, especially in areas where there is combined demand for potable water and electricity.

The research and development programmes which are being pursued aim towards meeting the challenges of enhanced safety, reliability and economic competitiveness. They should provide the basis for the development of advanced reactor types which could broaden the deployment of nuclear power and enlarge its contribution to energy strategies aiming towards alleviating greenhouse gas emissions.

## 4. NUCLEAR FUEL RESOURCES

Nuclear power plants operating at present are fuelled with uranium, natural or enriched, and to a much smaller extent with mixed fuel containing uranium and plutonium extracted from reprocessed nuclear fuel. The presently known high and medium grade uranium resources are sufficient to support the expected nuclear electricity generation up to about 2030. However, additional exploration and production capability development would be needed to ensure that the resources would be available in a timely manner.

As for most resources, uranium production and supply depends on the demand and on the market price. The uranium supply and demand relationships have changed significantly during the past decade. The uranium market has suffered from oversupply due to the slowing down of nuclear programmes in many countries, leading to a build-up of excess inventories now approaching some three years of consumption. Moreover, the dismantling of nuclear warheads could provide additional supply for civil applications, although some processing of the highly enriched uranium and plutonium contained in the weapons would be required before these materials could be used in nuclear power plants. As a response to the present situation of over supply, uranium production has decreased continuously during recent years and the average spot market price have reached its lowest historical value, in current dollars, at less than US \$7.5/lb $U_3O_8$.

Since the mid-sixties, the OECD/NEA and the IAEA, with the co-operation of their Member States, have published reports on uranium resources, production and demand. The known uranium resources, i.e., total Reasonably Assured Resources (RAR) and Estimated Additional Resources/Category I (EAR-I), recoverable at costs lower or equal to US \$130/kg U, are estimated at some 3 million tonnes U as of January 1, 1993 [16]. These estimates do not include the resources from Chile, China, India and most central and eastern European countries including Russia. Although resource data are limited in these countries, significant uranium resources are known to exist in Bulgaria, China, India, Romania and Russia.

There remains very good potential for the discovery of additional uranium resources of conventional type, as reflected by the estimates of Estimated Additional Resources/Category II (EAR-II) and Speculative Resources (SR). Based on reported estimates, this potential is about 13 million tonnes U. Nearly two thirds of this potential occurs in Australia, Canada, South Africa and the USA, while over one quarter occurs in China, Mongolia and Russia.

There are also large tonnage of unconventional resources of uranium, most of which are associated with marine phosphate deposits. Current production from such resources has been declining for economic reasons and is now limited, both geographically and in terms of output.

Sizeable exploration programmes are being conducted in Australia, Canada, France, India and the USA. A significant portion of the total exploration expenditure is funded by major uranium consuming countries such as France, Germany and Japan. Exploration activities are also reported to be substantial in China and Russia, although few details are available. This exploration effort is likely to provide additional knowledge of the amount of resources that may be made available for production should market requirements increase.

Since the late 1930s, cumulative production in countries outside eastern Europe, the former USSR and China has totalled about 1 million tonnes U, with most of it coming from the USA, Canada and South Africa, and to a lesser extent from Australia, France, Namibia and Niger. In addition significant quantities have been produced in China, central and eastern European countries, especially in the former German Democratic Republic and the former USSR, although reliable data on cumulative production in this area are not yet available. A significant part of this production has not been used, resulting in a build-up of inventories.

Worldwide, annual uranium requirements for civil applications are expected to increase from some 58 000 tonnes U in 1992 to about 75 000 tonnes U by the year 2010. Some utilities will continue to be able to supplement or offset their purchase requirements by draw down of excess inventories, and annual uranium production should remain below actual requirements until the desirable target level of stockpiles, i.e., some two years of consumption, will be reached. Taking into account the present production capabilities, the excess inventories and the possible contribution to civil supply by warhead dismantling, the use of nuclear power will not be constrained by uranium resource availability in the short and medium term, i.e., up to 2030.

In the long term, assuming that nuclear power would be deployed broadly as a means to alleviate greenhouse gas emissions from the electricity sector, advanced reactor types, including breeders, would have to be developed in order to better use the energy content of natural uranium. In this connection, it should be noted that, although they have not be developed to the level of commercial deployment, thorium fuelled reactors have been designed at the conceptual and experimental level. Thorium resources have not been evaluated with the same degree of certainty as uranium resources but low cost reserves are estimated to be of the order of 2.4 million tonnes. Eventually, the development of fusion reactors would provide an essentially renewable source of energy since the fuels for these reactors, deuterium and lithium, are abundant enough to alleviate any natural resource constraint to the expansion of electricity generation by nuclear fusion power plants.

## 5. BARRIERS TO AND INSTRUMENTS FOR IMPLEMENTATION

Nuclear power is a mature technology which has reached the stage of industrial and commercial development in many countries. However, its broader deployment will require instruments and policy measures in order to facilitate the implementation of nuclear programmes especially in developing countries where it could contribute substantially to alleviating environmental impacts from electricity generation.

It is difficult to define specific barriers to nuclear power deployment since each country has a different social and political context which may or may not be favourable to large, capital intensive, technically demanding technologies. However, the feedback from several decades of experience in nuclear programme planning and implementation, in both industrialised and developing countries, allows to the identification of the main obstacles to nuclear power development as well as the instruments required for the implementation nuclear projects. The main barriers to a broader development of nuclear power at present seem to be the lack of public acceptance and adequate licensing procedures in industrialised countries, and the lack of industrial infrastructures, qualified manpower and funding in developing countries.

Most of the barriers are of organisational and institutional nature [17]. Nevertheless, some technological and economic characteristics of nuclear power plants of the present generation do detract from their viability in certain countries. The large size nuclear units are an attractive option mainly for grid connected base load electricity generation in countries with rather high demand. The structure of nuclear generated electricity cost, with high up front investments makes it difficult to finance a nuclear project especially in developing countries. In this connection, the development of SMRs is likely to facilitate nuclear programme implementation in a larger number of countries, since they will be easier to finance and better adapted to medium size grids.

Nuclear power is a highly demanding technology in terms of quality assurance, qualified manpower and industrial infrastructures. The lack of sufficiently well trained staff for constructing, operating and maintaining nuclear facilities, could prevent the deployment of nuclear power, especially in developing countries. Since it takes time to put in place the required infrastructures, the rate of introduction of nuclear power should be adapted to the country's capabilities. The establishment of research centres is an important instrument for the satisfactory implementation of nuclear programmes. Research facilities are essential to support technical development incorporating feed-back from experience, and for training purposes. Exchange of experience, among all actors involved in nuclear power activities within a country and at the international level, is widely established as a good means of ensuring sound deployment of nuclear power. International co-operation aiming towards technology adaptation and transfer, and technical assistance in staff training will be a key factor in capacity building for nuclear power programme implementation in developing countries.

The primary difficulties in financing nuclear power projects are due to high investment costs and long construction lead times [18]. The large up-front capital cost may approach or even exceed the overall available credit limits for an individual utility or country. The lack of revenue from the project during the five to more than ten years of construction of a nuclear power plant, combined with the need to pay interest during this period, makes the financing even more difficult. In view of these issues, it is of critical importance that the financial plan be established carefully and that the investment climate be enhanced by the government and the owners of the plants. In particular, the construction schedule should be maintained and the electricity tariff structure should be adequate to ensure the financial strength of the utility.

Stability of regulatory rules and structure, which is important for any industrial activity, is essential in the case of nuclear power. Changes in licensing procedures and safety regulations, especially when they occur during the construction of nuclear units and have to be taken into account by modifying the design of the plant, have proven to be a burden for electric utilities. By modifying the rules of the game during the construction of a nuclear power plants, regulatory authorities have imposed additional costs and lead times to the plant owners which have, in some cases, jeopardised the economic competitiveness of nuclear power. Such instabilities in regulatory regimes have dissuaded utilities from ordering new nuclear units or even led them to cancel nuclear projects. The need for and benefits from long term planning and stable regulatory regime, which may be facilitated by the standardisation of nuclear units, are illustrated by the comparison of nuclear power programme development in France and the USA for example. Reactor orders stopped in the USA two years before the Three Mile Island accident, mainly for regulatory reasons.

The accomplishments of nuclear programmes in different countries shows that there are needs for a long term view given the long lead times for establishing the infrastructures, for large funding given the capital costs, and for standardised products to reduce costs and ensure safety [19]. This implies that centralised decision making bodies with independent safety organisations, supported by governments, would generally have more success in developing a cost-efficient and safe nuclear programme.

Public acceptance issues are not unique to nuclear power, and during recent years there has been a growing scepticism towards any kind of technical progress as well as a decrease in acceptance of large industrial facilities. Nuclear power is often rejected as a symbol of high technology, the consequences of which cannot be properly managed. One reason for reduced expectations of growth in nuclear capacity was the growing public concern over nuclear safety following the Three Mile Island and Chernobyl nuclear accidents, which made it difficult to obtain public acceptance for construction of new nuclear power plants in many countries. Some countries even changed their policies on nuclear power and decided to apply moratoria on additions to nuclear power plant capacity or to withdraw from nuclear generation. The Three Mile Island accident, although it has demonstrated the effectiveness of the defence-in-depth safety concept since it had no off-site consequences, reinforced the awareness of potential impacts of a severe nuclear accident. The Chernobyl accident, which highlighted the need for quality control and safety culture, resulted in some countries in political decisions, imposed by public opinion, on a moratorium of nuclear power development. The probabilistic risk assessment concept used for nuclear safety by the scientific community, and by designers and operators of nuclear units is difficult to understand for the layman, and is generally not used in other industrial sectors. Therefore, there is a special need for improving communication with the public on safety related issues. The role of international organisations, together with national authorities, is of utmost importance in this regard.

The emergence of international consensus on safety standards and practices and the adoption of worldwide agreed safety regimes should restore the confidence of the public in the ability of the nuclear industry to build and operate safely nuclear facilities. The adoption of long term policies for nuclear waste management and disposal, and the implementation of repositories for the final disposal of high level radioactive wastes should also contribute to enhance public acceptance of nuclear power. In this connection, international agreements and conventions are important instruments for facilitating the implementation of nuclear programmes. The conventions on "Early notification of a nuclear accident" and on "Assistance in the case of nuclear accident or radiological emergency" have been established and put into force after the Chernobyl accident. International agreements and conventions are also in place regarding radioactive waste disposal. A convention on the safety of nuclear power was adopted in June 1994 and signed by more than fifty States early in 1995. There is also a consensus that a convention should be worked out on the safe management and disposal of radioactive waste. Other conventions deal with the consequences of accidents in nuclear power plants. They establish a regime by which the operator of the plant, whether or not negligent or otherwise at fault, is liable to pay compensation to the victims of the accident, up to a liability limit laid down by national legislation. The Vienna Convention on nuclear liability and the Joint Protocol that links it with the Paris Convention are important parts of the international legal infrastructure that facilitates the development of nuclear power.

The potential use of nuclear materials and technology for non civil applications requires measures for preventing such uses while ensuring reliable and secure supply of nuclear fuel and adequate technology transfer and international market exchange for a sound development of nuclear programmes in all countries where it is a viable option.

The threat of nuclear proliferation is a major concern for decision makers and the public and has been a barrier to broader nuclear power deployment. With accelerated disarmament and the prospect of non-proliferation approaching universality, the peaceful use of nuclear power might eventually be de coupled in people's minds from the anxiety they have felt about nuclear weapons. Indeed, the fears expressed in the sixties that the number of nuclear weapons states could increase dramatically (c.f. the statement by the then-President of the United States of America, that the number of nuclear weapons states might soon reach between 15 and 20) have not materialised.

Early in the development of peaceful use of atomic energy, a series of international treaties have been created to ensure, as far as possible, that nuclear power will be used only for peaceful purposes and that all times, even in case of war, the public is protected. The Treaty on the Non-Proliferation of Nuclear Weapons (NPT), drafted in 1968 and entered into force in 1970, aims to prevent an increase in the number of nuclear-weapons States. It places conditions on the transfer of nuclear technology and materials, so as to prevent nuclear weapons from being developed by States other than those which were already nuclear powers at the time the treaty was drawn up. Coupled with the non-proliferation commitments in which States are enshrined, is the verification carried out on behalf of the international community in the framework of the international safeguards regime, by independent inspectors of the International Atomic Energy Agency (IAEA) [20]. There are also regional and bilateral inspection agreements such as those instituted by Euratom, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials, and various bilateral agreements concerning safeguards and co-operation between States. A further element is the system of controls which applies to exports of nuclear materials and equipment. This system aims at ensuring that when such items are exported Governments in the importing countries commit themselves to use them only for civil purposes. Under these conditions, supply for nuclear fuel and technologies needed for implementing a nuclear programme can be provided by international trade. Many countries are benefiting from imports of nuclear materials and equipment, and transfer of technology, while complying with their obligations under the international non-proliferation and safeguards regime.

The danger of criminal, including terrorist, diversion of nuclear material is addressed by the Convention on the Physical Protection of Nuclear Material (1980). Article 56 of Protocol I of the Geneva Convention prohibits attacks against "dams, dikes and nuclear electrical generating stations", if "severe losses among the civilian population" might result. Illicit trafficking in nuclear material became a matter of concern in 1993 and 1994. This matter has been discussed between governments and measures are underway to ensure that adequate systems are in place worldwide for accounting and controlling nuclear materials.

## 6. NUCLEAR POWER TECHNOLOGIES

The nuclear fuel cycle includes the nuclear power plant and the fuel cycle facilities from mining to repository for final disposal of wastes. This publication covers in detail technologies for nuclear reactors, which are essential in the assessment of performance and environmental aspects of the nuclear chain. The technologies for the different steps of the nuclear fuel chain are described briefly. Waste management and disposal issues are discussed separately since they deserve special attention in terms of the sustainability of nuclear power. At the power plant level, the different technologies currently used or under development, i.e., water cooled reactors, gas cooled reactors and liquid metal cooled reactors, are described. Fusion reactors, which are still at the stage of feasibility demonstration, are also described since they may become an important component of electricity generation mixes by the end of the next century.

### 6.1. NUCLEAR FISSION REACTORS

Although several types of reactors have been developed and have reached commercial deployment, some 80% of the current operating plants and more than 70% of the units under construction are light water reactors (LWRs) while some 5% of the nuclear capacity under operation or construction are heavy water reactors (HWRs). Both type of reactors have accumulated substantial operating experience and have proven to be economic, safe and reliable. Gas cooled reactors (GCRs) represent some 9% of the installed capacity but none are under construction. These reactors have been operated commercially in some countries with satisfactory results in terms of availability and safety. Liquid metal cooled reactors (LMRs) have been developed and operated in several countries. These reactors were conceived for breeding at the very beginning of nuclear power development, bearing in mind the need to utilise better the energy content of natural uranium. Since the uranium market situation does not call for breeder reactors in the short term, the present trend is to design LMRs for burning fissile material rather than for breeding. However, in view of the potential deployment of nuclear power as a means to alleviate greenhouse gas emissions from the electricity sector, the revival of breeder reactors could be an attractive option for extending the energy that can be extracted from natural uranium resources.

Advanced designs are been developed for all types of reactors, i.e., LWR, HWR, GCR and LMR. Research and development programmes are aiming towards designing power plants which will meet the challenge of improving technical and economic performance and enhancing the already high level of safety achieved by the nuclear units of the present generation. The main goals of the designers and manufacturers are to:

- improve the economics of nuclear power;
- reduce the residual risk of accident;
- reduce the emissions and residuals, including radioactive waste from routine operation of nuclear facilities;
- expand the resource base;
- broaden the range of applicability of nuclear power.

### 6.1.1. Water cooled reactors

Water cooled reactors, i.e., LWR and HWR, represent some 85% of the nuclear power plants presently connected to electrical networks worldwide. Their technical and economic performance has proven to be highly satisfactory. A high degree of availability has been achieved over the last 5 years, with annual average load factors above 80% in the majority of the countries were these type of reactors are in operation.

Light water reactors have a mature infrastructure and regulatory base in several countries. On going developments are focusing on large size units with evolutionary designs resulting from continuous upgrading and improvements based upon feed back from experience gained in the operating and maintenance of the reactors of the present generation. New concepts are also emerging partly as a reaction to the complexity of the design which came from the successive overlaying of new regulatory requirements in many countries [21, 22].

The main objectives of the evolutionary approach, which is already leading to considerable improvement of reactor designs, are to increase the safety margins, to reduce construction, operating and maintenance costs, and to reduce radiation doses for operators. Construction cost reduction is obtained by streamlining designs, shortening construction lead times through standardisation, which should also facilitate licensing procedures. The French N4 model, a 1400 MW(e) PWR, which is under construction, derives directly from the standardised P4 series, 1300 MW(e) PWRs, while achieving a 5% construction cost reduction. Another example of these new designs is the advanced BWR 1350 MW(e), two units of which have been ordered by Tokyo Electric Power Company (Japan) and are expected to be operational in 1996 and 1998. It has a volume of about 70% of previous BWRs of similar size, and uses internal coolant pumps to reduce piping and welding and the frequency of in-service inspection. These characteristics are reducing construction costs and, together with design features oriented to easier service and maintenance, will decrease potential radiation exposure to workers. The Westinghouse-Mitsubishi APWR 1350 MW(e), the British Sizewell-B PWR 1250 MW(e), the ABB-Combustion Engineering System-80-plus BWR 1300 MW(e), the General

Electric-Hitachi-Toshiba ABWR 1360 MW(e) and the Russian PWR 1000 MW(e) are further examples of the large size evolutionary advanced LWRs.

All water cooled reactors rely to some extent on so-called passive safety features. Some have negative feedback between reactivity and temperature and between reactivity and void volume and some have circulation of cooling water by convection in accident situations. The latter aspects can be exploited more readily in designs which are smaller physically and have lower power densities. The developers of these concepts indicate construction costs reductions of some 25% as compared to current designs. Cost reductions will be obtained by shortening construction lead times to 3 to 4 years, through a high degree of factory assembly of systems and sub-systems and stabilised licensing requirements. Typically these designs feature large water pools located above the core to be fed into it by gravity in case of an accident. The simplicity of design is indicated by Westinghouse's suggestion that the AP600 will need about half the concrete, half the large pumps and heat exchangers, 60% fewer valves, 60% fewer pipes and 80% less control cables than a 600 MW(e) reactor of current design. These reactors already exceed the present safety requirements and could therefore be licensed or certified by the mid-1990s. Their stage of development is such that, according to the manufacturers, they could be available for commercial deployment by the turn of the century.

Designs incorporating even more innovative features are developed in some countries on the ground that evolutionary improvements will not suffice to provide the demonstrable safety which investors and the public wants. Several drastically new designs have been conceived to meet these expected requirements. They include the ABB's Process Inherent Ultimate Safety reactor (PIUS), the University of Tokyo's Intrinsically Safe Economical Reactor, the JAERI's System Integrated Pressurised Water Reactor and the Safe Integral Reactor concept developed by an Anglo-American group. All these reactor concepts have a much greater reliance on thermo-hydraulic phenomena to ensure safety, with the intention of virtually eliminating any possibility of a core melt accident and, therefore, the need for the operator to prevent that type of occurrence. The revolutionary concepts, which will require prototype or demonstration reactors before they can be commercially deployed, cannot be expected to be available before the beginning of the next century. Although there are uncertainties on the costs of revolutionary concepts, they are expected to be similar to those of reactors of the present generation. For example, ABB estimated that the overall cost of electricity generated from a 630-650 MW(e) PIUS would be close to that for a 700 MW(e) BWR plant.

Development programmes for heavy water reactors are carried out mainly in Canada but also in India and Japan. As in the case of LWRs, new HWR designs are aiming towards cost reduction and enhanced safety and performance. Examples of advanced HWRs are the 450 MW(e) CANDU 3, the 665 MW(e) CANDU 6 MK2, the 500 MW(e) Indian HWR, and the 380 MW(e) ARGOS jointly developed by Argentina and Germany. In Japan, a heavy water moderated, boiling water cooled, pressure tube reactor (ATR) has been developed. In the Republic of Korea a programme for the development of a 900 MW(e) HWR using slightly enriched uranium is being carried out jointly with Canada.

The concepts presented above aim at improved safety and economics, including improved protection of the investments. Other concepts are being developed with the objective of enhancing the use of nuclear power for non-electrical applications. There is already some use of process heat from the Canadian heavy water reactor type (CANDU) at Bruce in Ontario (Canada). In Switzerland, waste heat from BWRs is used for district heating. However, the steam temperature produced by present water cooled reactors places some limits on their application in the field of process heat. Moreover, they are not well adapted for district heating since their capacity is generally too large to allow their construction in highly populated urban areas. Canada has developed and marketed a 10 MW(e) passively safe reactor, SES-10, specifically for space heating markets, which should be licensable for siting very close to heat loads, e.g., in a large hospital.

Developments to extend the resource base are pursued, aiming towards reducing uranium consumption per unit of electricity generated through improved fuel design and management, changes in reactor designs, and fuel substitution. Improved fuel management and design can lead to greater burnup of the fuel with extension from the currently common 33 MW· d/kg to 50 MW· d/kg or higher without reducing safety. Estimates vary as to the magnitude of the uranium savings, but might be in of some 10 to 15% by 2000 as compared to the rate of consumption experienced in the eighties. The use of higher burnup with longer operating cycles can also improve the overall economics by some US $2 to 4 million per fuel cycle, or roughly 10% of the fuel cycle cost. The use of less absorbing materials in the fuel and core can lead to economy in the use of neutrons, hence lower enrichment requirement and natural uranium feed stock use. Continuous progress is being made in this way.

The recycling of plutonium extracted from reprocessed uranium fuel in mixed oxide fuel (MOX) for LWRs is another means to increase the amount energy extracted from natural uranium. Current LWRs can take up to 30% of their fuel as MOX, typically containing 5% of plutonium oxide, without departing from normal safety and control requirements. Safety authorisations for using MOX fuel have already been given in several countries, and there are plans to use MOX in some 40 to 45 reactors in OECD countries.

Enhanced use of the energy content of nuclear fuel can also be obtained by high conversion reactors in which a more energetic neutron flux drives the nuclear reaction further, producing internally and consuming more plutonium than in current uranium fuelled LWRs. On the basis of current design studies, these reactors could be developed by only partial replacement of core internals. The increase in capital costs would be of some 1 to 2%, as compared to present LWRs, and the fuel cycle costs would be reduced at least by 10%. Such designs could be implemented within a decade if incentive for their development were to be provided by an increase in uranium prices. More advanced concepts, still in the testing phase, would provide flexibility for using plutonium and uranium, and would reduce specific uranium requirements by up to 33%.

### 6.1.2. Gas cooled reactors

The first nuclear power units put into operation in western Europe were gas cooled reactors. However, only the United Kingdom has used them to any significant extent and experience has been mixed, although the most recent ones are reported to be operating well and economically. Interest in increasing the efficiency of GCRs by using higher operating temperatures led to the NEA's DRAGON project, which terminated in 1972 after considerable experience on new fuel types had been gained. Based partly upon this work, the development of high temperature gas cooled reactors (HTGRs) has been carried out forward in the Federal Republic of Germany with AVR and THTR, and in the USA with the Fort St. Vrain power plant. Japan has started the construction of a high temperature test reactor [23].

In Germany, AVR operated successfully from 1966 to 1988. Using helium as the coolant, outlet temperatures of 950°C were obtained and efforts were devoted to fuel development. The fuel elements were uranium dioxide spheres of about 0.4 mm diameter encapsulated in layers of pyrolytic carbon and silicon carbide before being dispersed in a graphite matrix, and the core consisted of a graphite and steel barrel (hence the term "pebble-bed reactor"). The reactor was refuelled on-line. In the USA, the fuel particles were compacted into channels in hexagonal graphite prisms, pierced by cooling channels and placed into a graphite block. It has been demonstrated that there is a very low failure rate of these fuel elements and for capacities of 200 to 350 MW(th), and core power density from 3 to 6 W/cm$^3$, it can be confidently expected that no emergency conditions can produce temperatures high enough, i.e., above 1600°C, to increase the fuel failure rate markedly. Fission products were retained within the fuel elements in all conditions so far conceived, so that off-site radioactive pollution after an incident is negligible. Fission product retention also contributed to reducing the operator dose under normal operation to about one-tenth of that routinely achieved for American LWRs. Radioactive release from this type of high temperature gas cooled reactors can be limited to such a degree that they can be implemented in large industrial complexes.

The relatively small size of these reactors implies some loss of economies of scale, which might be offset by benefits in term of capability to increase capacity in relatively small increments and to have multiple plants providing high security of reliable electricity or heat supply. Levelised electricity generation costs, calculated for a commissioning in 2010, show that the American design, for a plant of 226 MW(e) constituted by two modules of 133 MW(e), would be competitive with a conventional coal fired power plant of similar size, assuming a coal price of US $1.86/GJ in 2010, increasing by 1% per year.

In terms of extending the resource base, HTGRs using mixed thorium and highly enriched uranium fuel can achieve, without reprocessing, the same natural uranium savings than LWRs using recycled plutonium in MOX fuel. Although considerable experience has been accumulated on thorium/highly enriched uranium fuel cycle, some policy and technical issues, such as supply of highly enriched uranium fuel and waste management and disposal, have not been fully addressed. Moreover, the present uranium price does not provide incentive for the development of alternative nuclear fuel cycles. Therefore, development of HTGRs has been discontinued in Germany. In the USA, a limited research effort, supported by governmental funding, is maintained on the development of a thorium/20% enriched uranium fuel cycle for modular high temperature gas cooled reactors (MHTGRs).

### 6.1.3. Liquid metal cooled reactors

Breeder reactors using liquid metal coolant were conceived in the very early years of the development of nuclear power, with the objective of ensuring a better utilisation of the energy content of natural uranium. The introduction of breeder reactors has been postponed in view of the limited rate of increase of nuclear power capacity worldwide, and of the present market prices of natural uranium. However, presently expected growth of nuclear electricity generation indicates that known uranium resources recoverable at costs lower than US $130/kg U will have been committed to reactor use by the middle of the next century. If nuclear power were to be more broadly deployed in order to avoid carbon dioxide emissions, uranium resources would be committed earlier, leading to potential major increase in uranium price before 2030. Since many of the nuclear power plants under operation will reach the end of their life time in the period 2010 to 2030, their owners will have to choose candidate technologies for their replacement by the end of the century. In this connection, research and development on breeder reactors is aiming towards enhancing their competitiveness as compared to advanced LWRs operated with once-through or reprocessing and recycling fuel cycle [24]. The benefits of breeders with regard to radioactive waste management and disposal are also being evaluated and taken into account in comparative assessment of different nuclear fission reactors. Furthermore, the use of LMRs for burning plutonium arising from dismantling of nuclear weapons is investigated.

Prototype and commercial scale liquid metal fast breeder reactors have been developed in seven countries and experience has been accumulated in their design, operation and maintenance. France has been operating a 233 MW(e) unit, Phenix, from 1973, and has built, jointly with other European countries, a unit of 1200 MW(e), Superphenix. In the United Kingdom, a 250 MW(e) prototype has been in operation since 1976 at Dounreay. Germany built, but did not operate, a 295 MW(e) unit, SNR-300. All three countries have designed concepts for a power station in the range 1300 to 1500 MW(e) using a pool of sodium as coolant, and have joined their research, development and design efforts, since 1988, into a co-operative European programme. The former Soviet Union has an important programme on breeder reactor development. BN-350, now in Kazakhstan, was put into commercial operation in 1973, BN-600 in 1981, and the two 750 MW(e) units are under construction in the region of Ural. In Japan, a 250 MW(e) unit, Monju, was put into commercial operation early in 1994. In the USA, a 65 MW(e) unit, Enrico-Fermi, was in operation from 1963 to 1972, fuel and coolant test rigs were operated over the last 30 years and a concept of modular LMR, providing 1395 MW(e) from three groups each of three modules, has been developed.

Both the pool and loop types of plant have been designed to have good safety margins so that limited or no operator action is required to prevent coolant boiling or fuel melting in accident situations. Ongoing research and development efforts are aiming mainly towards increasing fuel burnup, enhancing safety and reducing construction costs, which are at present some 50% higher than for LWRs of the same size. Long term objectives for fuel burnup range from 150 to 200 MW·d/kg. Efficiency and safety enhancements are expected through better control of impurities in the coolant, greater understanding of core physics, thermo-hydraulics, including passive decay heat removal, and material properties. French and German studies suggest that considerable savings can be made in construction costs by a 20% to 30% reduction of the weight of materials for the nuclear steam supply system (NSSS). Further savings can be made in the balance of plant by enhancing reliance on passive safety features in the NSSS.

In the United Kingdom and France, closure of the breeder fuel cycle has already been demonstrated with more than 99% recovery of plutonium, using the PUREX chemical separation process on the oxide fuel. Fuel cycle costs are similar to those of LWRs operated once-through, with burnup levels already achieved in the present generation of LMRs, and at the current prices of uranium and fuel cycle services. The development of breeders on a broader scale would lead to reprocessing cost reduction and ongoing research efforts should bring efficiency improvement within the fuel cycle processes.

An alternative fuel cycle has been explored in the USA, using a metal fuel (plutonium, uranium, zirconium alloy) which would be reprocessed by melting and electrolytic separation. Experience with test rigs and research reactors suggest that this fuel can be expected to be highly reliable in operation, with test burnups of 170 MW·d/kg already achieved. Experiments in test reactors have demonstrated that the thermal conduction and neutronic characteristics of the metal fuel provide wide safety margins to coolant boiling and fuel failure in case of loss of coolant or loss of heat sink. The developers of this design indicate that by integrating a reactor, a pyrometallurgical reprocessing plant and a fuel fabrication unit on one site (the IFR concept), the fuel cycle costs would be considerably less than for the oxide/PUREX cycle.

Liquid metal cooled reactors operated with closed fuel cycle involving reprocessing which reduces the volume of highly radioactive wastes and, therefore, facilitates and reduce the costs for final disposal of these wastes. With the fast breeder reactors, the actinides produced may be retained in the recycled fuel and consumed so that the remaining waste decays to background radioactivity levels within about 300 years, instead of thousands of years as is the case with high level waste from other reactors.

## 6.2. NUCLEAR FUEL CYCLE TECHNOLOGIES

Nuclear fuel cycle activities cover mining and milling of natural uranium, conversion and enrichment for reactors using enriched uranium, fabrication of fuel elements and spent fuel management and disposal. The back end of the nuclear fuel cycle may be once through, i.e., with final disposal of conditioned spent fuel, or closed, i.e., with reprocessing of spent fuel, recycling of fissile materials and final disposal of residual high level radioactive waste. Both options have been developed at the commercial scale up to interim storage of high level waste. Experience accumulated in countries operating nuclear power fuel cycle facilities have demonstrated that all these activities can be carried out reliably and safely [25]. Scientific and technical solutions for final disposal of high level waste have been designed and tested at the laboratory level and are progressively implemented at the industrial scale in different countries.

Research and development programmes in the field of nuclear fuel cycle activities are aiming towards efficiency enhancement, cost reduction and improving further the already satisfactory performance in terms of health and environmental protection. Since fuel cycle costs account for about one fifth of total levelised nuclear electricity generation costs, cost reduction have only a marginal impact on economic competitiveness of nuclear power. Nevertheless, there are incentives on the nuclear fuel service market for the development of more efficient processes leading to material savings and cost reductions. The implementation in a number of countries of more stringent safety, health and environmental protection regulations are also supporting efforts to enhance the efficiency of the industrial processes in order to reduce losses, emissions and residuals.

Uranium exploration and extraction technologies progressed significantly up to the mid-1970s when market conditions were calling for expanding the resource base and production capabilities. More recently, efforts have focused on exploration targeted on resources with low production costs, higher efficiency in recovery rates from low grade ores, rehabilitation of mining sites and reduction of radioactive doses to workers. Economic processes for recovering uranium from very low grade resources have been developed and used, e.g., at 0.03% in the Rossing mine in exploitation in Namibia. Technologies for exploitation of the more costly known resources are available although they may need further adaptation to be implemented whenever the market forces will justify the recovery of lower grade resources particularly when they are not associated with other economically useful metals.

Exploration, mining and milling technologies for thorium will not differ significantly from those currently used and would be available in time at the industrial scale if thorium fuelled reactors, which could offer an attractive alternative to uranium fuelled reactors [26], were to be developed.

Most of the nuclear power plants in operation require a fuel containing slightly enriched uranium. Two technical processes for the enrichment in the fissile isotope $^{235}U$, from its natural level of 0.7% of the total mass of uranium to some 2.5% to 5%, have been developed and are used in industrial facilities, i.e., gaseous diffusion and ultra-centrifugation. The centrifugation process, especially when using recently developed ultra high speed centrifuges, is more efficient in terms of energy consumption and economically more attractive than gaseous diffusion for medium size capacities. For both technologies, production costs are lower than the current market prices of about US $100/kg separative work unit. However, new processes are under development aiming towards reduction of production costs, modularity and enhanced flexibility of industrial facilities. Although chemical processes have been studied and demonstrated, in particular in France and Japan, up to the prototype stage, research in this field has been practically abandoned owing to the lack of market incentive. Major research and development programmes, especially in France, Japan and the USA, focus at present on laser processes, with emphasis on atomic vapour laser isotope separation (AVLIS). In this process $^{235}U$ atoms are selectively excited by laser beams. Feasibility studies and testing at the laboratory level indicate that industrial facilities based on the AVLIS process could be commissioned by the turn of the century and would have production costs, for the first units of the order of US $ 70/kg separative work unit. The selectivity and efficiency of the process would allow in principle a significant lowering of the tail assays of enrichment plants, thus increasing the amount of electricity generated per unit of natural uranium used in fission reactors, i.e., extending further the resource base for nuclear power. However, the economic competitiveness of low tail assays as compared to other uranium resource base extension has not been fully demonstrated.

All fuel manufacturers strive to improve the reliability and efficient use of nuclear fuel elements by changes in materials and configuration. Reactor manufacturers and utilities contribute by modifying the operating cycle and core management to obtain higher burnup of fuels. The effect of this kind of activity can be illustrated by a 10% fuel cost saving achieved by Electricité de France in its 900 MW(e) reactors by increasing fuel enrichment and burnup. Worthwhile economies can be achieved by operating a reactor consistently close to its operating design limits so the introduction of improved in-core instrumentation is also considered important, as is the improvement of reactivity control by introduction of burnable poisons into the fuel.

## 6.3. SPENT FUEL AND WASTE MANAGEMENT

The operation, maintenance and decommissioning of nuclear power plants and fuel cycle facilities produce radioactive wastes in which there are varying degrees of contamination by a range of radioactive isotopes.

The objective of radioactive waste management is to protect both man and the environment from the emission of ionising radiation from these waste. The risk associated with ionising radiation has been thoroughly evaluated by scientists, medical professionals and engineers over many decades and codified by the International Commission on Radiological Protection (ICRP). Exposure to ionising radiation may occur as a result of release of radioactive materials into the human living environment. In these respects, they have the same intake and exposure routes as many other hazardous substances. Only the additional route, that of direct exposure of the body to external radiation, is unique to radio nuclides. Current concepts for disposing of radioactive wastes, call for a multiple barrier approach with a number of interrelated, often redundant barriers between the waste and the human environment. The performance of the engineered barriers as well as the necessary geological conditions for implementing radioactive waste repositories have been extensively studied as well as the method for conditioning the various radioactive wastes before disposal.

The total volumes of radioactive waste arising from nuclear electricity generation are rather small as compared to hazardous wastes from some other electricity generation chains [27]. More than 99% of the total radioactivity of wastes arising from nuclear electricity generation is contained into high level wastes (HLW). These HLW are either in the form of a few tens of cubic metres of conditioned spent fuel or in the form a few cubic metres of vitrified waste when spent fuel is reprocessed. The remaining 1% of the generated activity is contained in low or intermediate level wastes (LLW, ILW), the volume of which ranges around 500 cubic metres per GW(e)·year after conditioning [28]. A survey in the United Kingdom indicated that in one year more than 4 million cubic metres of toxic wastes are produced of which only 1.1% is radioactive, and only 0.1% of the volume of these radioactive wastes is high level radioactive waste. With regard to decommissioning, the NEA has conducted an international programme for the exchange of scientific and technical information on ongoing activities. Twenty decommissioning projects are currently active [29] and a few of them, which have reached the stage of availability of the site for public use, demonstrate by concrete experience that sites used for nuclear facilities can be returned to the state prior to the implementation and operation of the facility.

A number of conditioning processes are available for LLW and ILW, which have been demonstrated over nearly thirty years of experience, and are currently used in countries which have developed nuclear programmes. The technical problems of disposing of these wastes arise mainly from their volume. Therefore, attention is being given to compacting methods, e.g., electrolytic refining to separate radioactive isotopes from steel structures recovered from reactor cores, and incineration of low level wastes, such as paper and clothing. Practices for the disposal of low and intermediate level wastes include a number of options adopted or under consideration in different countries. According to the type of conditioning, local conditions and national policies, low and intermediate level wastes may be disposed of in near surface, intermediate depth or deep geological formation repositories. From 1967 to 1981, low level wastes were dumped at a monitored site in the North Atlantic. Although the detailed monitoring had not detected any release of radiation and the practice was judged technically sound by the NEA's Surveillance Mechanism, it was decided at the meeting of the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, held in 1982, to suspend these operations and there is now in place a ban on all further sea dumping.

Two options are available for spent fuel management and disposal: direct disposal of suitably packaged spent fuel as waste; and reprocessing for recovery and recycling of uranium and plutonium, and conditioning of residual high level waste for their disposal. No high level waste repository has been implemented at present because there is no physical need nor economic incentive and further analysis of the different technical options available is desirable in order to adopt optimal strategies. In the mean time, spent fuel and high level waste from reprocessing plants are kept in interim storage facilities on nuclear power plant or reprocessing facility sites. There is a consensus among experts that safe geological disposal of HLW, including spent fuel, is technically feasible and several countries are pursuing studies aiming towards the implementation of final repositories early in the next century. The construction of final repositories in countries such as France, Sweden and the USA, which have large nuclear programmes will demonstrate the ability of the industry to implement satisfactory solutions for long term management and disposal of high level wastes.

The safety assessment of radioactive waste repositories in the long term has been extensively studied in a number of countries and by international expert groups. On the basis of the many research programmes completed or in progress, the NEA's Radioactive Waste Management Committee has reaffirmed its confidence in the safety and feasibility of geological disposal of radioactive wastes. However, even when waste repositories have been operated for a few years it will not be possible to assert solely from the experience gained that the repository will perform as required in the very long term required for the radioactive waste to decay to the level of natural background radioactivity. Therefore, in order to complement data collected from experience, methodologies and models have been developed for simulating and assessing the behaviour and performance of repositories. Data bases have also been established on relevant physical and chemical parameters, e.g., thermochemical and sorption data, related to geological formations considered suitable for the implementation of final disposal sites. The performance assessments extend to consideration of human intrusion into a waste repository. Recently the NEA and the IAEA, with the endorsement of experts of the Commission of the European Communities, issued a Collective Opinion based on a review of experience with safety assessment of waste disposal systems. They considered "that appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations" [30].

Transportation of radioactive wastes from the production sites to the treatment and conditioning sites, and finally to the disposal sites has been carried out with very good safety record over the last decades. Over 150 000 shipments have been made by road, rail and sea within and between OECD countries over a period of 30 years with no incidents leading to significant exposure to the public [31].

## 6.4. FUSION REACTORS

Fusion power has the potential of becoming a significant energy source in the long term. Fusion reactors, which would not produce atmospheric emissions, could contribute to alleviating environmental impacts of the electricity sector and in particular the risks for global climate change. The primary fuels for fusion reactors, i.e., deuterium and lithium, are so abundant in nature that fusion would practically be an inexhaustible source of energy. As a result, nuclear fusion could enhance energy supply security and become an important component of electricity generation systems worldwide.

Nuclear fusion is still under development, and scientific and technical issues remain to be addressed in order to demonstrate the feasibility of self-sustaining fusion reactions leading to net energy production in industrial scale facilities. The three main stages of demonstration, i.e., scientific, technical and industrial feasibility are likely to require rather long lead times which could not allow the stage of commercial deployment to be reached before the last quarter of the next century. The pace of research and development efforts is governed by the capabilities for building and operating in sequence of a number of large devices, from engineering test reactor, through demonstration reactors to commercial reactors, and by the ability to solve technical issues regarding power plants and supporting fuel cycle facilities. Historically, the scale of the facilities required for the development of fusion power and the sequential nature of steps have been an important factor in determining the pace of fusion development.

The energy released by fusion reactions is very large, about ten times greater than in typical fission reactions, per unit of nuclear fuel. Since the electric charges of the nuclei provide strong repulsive forces, the energy of the particles must be very high for the fusion reaction to occur at a sufficient and sustained rate. This can be achieved in a high temperature gas or plasma, by allowing sufficient residence time for the particles to collide. The fusion fuel of primary interest to achieve net power production is a mixture of deuterium (D) and tritium (T) in equal proportion. In a D–T reactor, the neutrons produced by the fusion reaction will heat the blanket, and coolants circulating within the blanket and the plasma transfer the heat out of the reactor area to produce steam and generate electricity. The blanket also serves the purpose of producing the tritium fuel required by the reactor, once the start-up inventory has been used. Lithium, which is transformed to tritium by neutron bombardment is the chemical element used in the blanket. Although deuterium–deuterium reactions and deuterium–helium$_3$ reactions could also be considered that have not been investigated in view of fusion reactor development.

There are two basically different approaches to thermonuclear fusion: high magnetic field confinement fusion and inertial confinement fusion [32]. Three toroidal confinement devices have been developed for magnetic confinement fusion, i.e. the tokamak, the stellarator and the reversed field pinch, with most of the technological effort concentrating on tokamaks. In principle, open magnetic configurations could be much less sophisticated and technically more attractive than closed configurations. However, research on open magnetic configurations has been practically abandoned since technological problems could not be solved at present. In the inertial confinement fusion approach, a high energy beam of light (photons generated by a laser) or of particles (ions generated by a particle accelerator) is used to rapidly heat the surface of a spherical pellet, thus forming a thin plasma envelope. The high energy laser or the particle beam used to heat the pellet and to initiate the fusion process is called the driver.

A fusion reactor based on the tokamak concept would consist of a toroidal reaction chamber, surrounded by a lithium-containing blanket for power extraction and tritium breeding; both are embedded in a magnetic field produced by toroidally arranged coils. Deuterium and lithium are the basic fuel constituents. Since tritium is bred in-situ, there would be no need for an external fuel factory. The power would be extracted from the high temperature steam produced in the blanket by a heat exchanger coupled to a conventional electricity generating plant.

Using the most powerful experimental devices available, development in the field of magnetic field confinement fusion has reached a stage in which plasma conditions are close to those needed for reactor operation. Progress towards a sustained fusion reaction is measured by comparing the equivalent fusion power produced to the rate of heat loss from the plasma. Tokamak experiments have increased this ratio by a factor of over a million during the last 20 years, by raising plasma temperatures and improving the quality of heat insulation. A factor of approximately 15 remains to be achieved to reach the ignition point, in which the plasma keeps itself hot by its own fusion reactions, while generating additional energy which can potentially be extracted from the system.

Magnetic confinement fusion research is carried out in a number of countries, mainly within the framework of international co-operation programmes. The world's effort in magnetic confinement fusion research amounts to more than US $1000 million per year. The International Thermonuclear Experimental Reactor (ITER) brings together the efforts of a large number of countries, including the European Community, Japan, the Russian Federation, Sweden, Switzerland and the USA. The engineering design activities being conducted within ITER shall produce a detailed, complete and fully integrated engineering design of a fusion reactor [33]. Canada, China and some 25 other countries are pursuing rather modest fusion research programmes. The present objectives are to complete the scientific basis for the tokamak approach, to optimise the confinement concept, and to address the engineering issues for the design of fusion power plants. Based on data currently being acquired, devices are now being designed to demonstrate burning plasma conditions and to allow testing of reactor components. The ITER programme is expected to lead to the construction of an international experimental facility early in the next century. It should then be followed by a demonstration reactor to prove that fusion power can be developed at the industrial scale and would be reliable, safe and economically competitive.

A conceptual fusion reactor based on inertial confinement utilises fusion energy from a very dense and high temperature plasma generated in the centre of a spherical reactor chamber with a blanket containing lithium. The ultimate objective of inertial confinement fusion programmes is to demonstrate that a mixture of deuterium and tritium fuel in a small capsule can be compressed and sufficiently heated by a high energy laser beam or by ions generated by a particle accelerator, to undergo an efficient fusion reaction while still being confined by its own inertia. Inertial fusion is less mature than magnetic confinement; however, progress in inertial fusion has been rapid since the early 1960s. Key issues to be addressed in order to demonstrate the feasibility of inertial confinement fusion at the industrial level are the pellet design and construction, and the driver (laser or particle accelerator) efficiency.

Fusion power research and development is mainly aiming towards large scale base load electricity generation plants. However, nuclear fusion is a very high temperature technology, which could be used for process heat supply in chemical and other industrial facilities. This includes the possible production of hydrogen or hydrocarbons. Present concepts are limited to extracting fusion energy for electric generation via a heat exchanger from a blanket surrounding the reaction chamber. Predicted operating temperatures of steam or helium working fluids should allow Rankine cycle thermal conversion efficiencies of 40%, and the development of advanced materials would lead to higher efficiencies. These enhancements could widen the range of applications of nuclear fusion applicability.

Fusion power would offer some advantages in terms of extension of the energy resource base, environmental and safety aspects. The volume of radioactive waste produced during the lifetime of a fusion reactor, due to regular replacements of components and decommissioning of the plants, would be comparable to that of a similar size fission reactor of the current generation. However, no actinides and no volatile reaction products are produced in fusion and, therefore, the processing and disposal of radioactive waste would be easier than in the case of fission reactors.

## 7. ECONOMICS

The cost of generating electricity remains the cornerstone for assessing different technologies and taking decisions for implementing supply strategies. However, the increasing awareness of environmental issues has changed the approach from the traditional least cost planning to a more comprehensive assessment of all the health, environmental and social effects. Methodologies are being developed aiming towards internalising, as far as possible within an integrated analytical framework, the full costs and benefits to society of different technological options. The economic assessment of nuclear power given in this section covers both the direct costs and the so called externalities, which are generally not incorporated in classic economic comparisons.

### 7.1. DIRECT COSTS

Although the competitiveness of nuclear power has been reduced recently by the decline in fossil fuel prices, nuclear power plants continue to be cheaper than fossil fuelled power plants for base load electricity generation in most countries which have developed and implemented nuclear power programmes. Nuclear power is more competitive in countries where indigenous fossil fuel and hydropower resources are scarce or expensive to exploit. The competitiveness of nuclear power is also enhanced by the size and consistency of the national nuclear programmes, as demonstrated by the experience in countries such as France, Japan and the Republic of Korea. In countries having access to low cost fossil fuels, nuclear power is less attractive. Moreover, the relatively short lead times and low investment costs of small size fossil fired power plants offer more flexibility to utilities in their technical and financial planning. In this connection, the development of SMRs could enhance the competitiveness of nuclear power especially in developing countries.

The IAEA has carried out a review of recent experience of nuclear and conventional base load electricity generation costs in several countries, based upon information provided by Member States [34]. The construction costs of nuclear power plants which were built in the last decade varied from about 1000 to 3000 US $/kW(e) in the countries surveyed, i.e., Canada, former Czechoslovakia, Hungary, India, Republic of Korea and Spain. Nuclear fuel cycle costs were found to vary from about 4 to 12 US mills/kW·h, and operation and maintenance costs from 4 to 13 US mills/kW·h, resulting in electricity generating costs of 25 to 60 US mills/kW·h. A similar range of about 20 to 60 US mills/kW·h was found for coal based generation in the same countries. Worldwide generation cost experience spans a considerably wider range from very low costs at old, largely depreciated plants to very high costs at plants which suffered long construction delay and/or poor operating performance. However, the generation costs of nuclear and coal fired plants of the same vintage and built in the same country are generally close, with nuclear power plants mostly competing well with fossil fired plants, although some by a rather small margin.

Operation and maintenance costs for nuclear power plants increased in the last decade from about 3.5 to 6 US mills/kW·h to about 5 to 16 US mills/kW·h in most of the OECD countries, for a variety of reasons, including refurbishment requirements in some countries and, in others, regulatory change which led to significantly higher staffing levels and hardware modifications or additions.

Nuclear fuel cycle costs have decreased by some 40% over the last decade due to improved fuel and reactor performance factors and to lower prices of materials and services especially in the front end of the fuel cycle, e.g., natural uranium and enrichment services [35]. The costs of some stages of the back end of the fuel cycle, including decommissioning of nuclear power plants and fuel cycle facilities and radioactive waste management, remain uncertain in the absence of broad industrial experience [36]. However, these uncertainties have no major impact on the total cost of nuclear electricity generation since the main component of this cost is the investment.

Technological progress will enhance the performance of nuclear power plants and, based upon the accumulated experience, new units under development that will be connected to electrical grid in the coming decade are expected to have lower costs. Capital cost reductions could be obtained inter alia by standardisation of designs and streamlining of licensing procedures that reduce construction lead times. Recent studies on projected costs for base load electricity generation show that nuclear power will remain competitive with coal fired power plants in a number of countries and that electricity generated by renewable sources will not reach competitiveness for grid connected electricity generation within the coming two or three decades.

Every third year since 1982, the NEA, lately in co-operation with International Energy Agency (IEA) of OECD, the International Union of Producers and Distributors of Electrical Energy (UNIPEDE) and the IAEA, has conducted a study of the projected costs for electricity generation covering nuclear power, coal and gas fired power plants, and, as far as information is available, power plants using renewable sources. The data are provided by utilities or government agencies from OECD and non-OECD countries. A common methodology, based upon the life time levelised cost calculation, is used to assess and compare the cost of electricity generation by different technologies. method used is the levelised cost method. This method provides cost values incorporating all the steps of energy chains, including waste management and decommissioning. Assumptions regarding discount rates, load factors and life time of the power plants are harmonised in order to allow a consistent comparison between technologies and among countries.

In almost all countries that have provided data over the past decade, projected nuclear generation costs for LWRs and PHWRs have shown greater stability over time than the projected cost of generation from fossil fuels. Indeed, in most cases, projected nuclear costs, on a common price basis and standardised discount rates, lifetimes and load factors, have not varied by more than around 10 per cent, as reductions in projected nuclear fuel costs have offset any projected increases in nuclear investment and operations costs. However, the sharp decrease in fossil fuel prices since the mid-1980s has reduced the competitive margin of nuclear power in many countries.

The latest study, published in 1993 [37], focused on plants that could be commercially available for commissioning in the year 2000 or shortly thereafter. Information was provided by 22 countries mainly on PWRs, BWRs, HWRs, pulverised fuel coal burning plants, some fluidized bed coal burning plants and gas combined cycle plants. Relatively few data have been provided on other advanced technologies, especially on electricity generated from renewable energy sources. The relatively scarce data provided on renewable sources suggest that in general they will remain more expensive than fossil fired power plants for base load grid connected electricity generation. However, they may provide economic fuel saving in remote areas where they would substitute to diesel generation.

The study has revealed an upward shift over the past three years in the discount rates used by some governments and utilities. Any such shift increases the levelised cost of capital intensive technologies, like nuclear power or most renewable energy sources, relative to less capital intensive technologies like gas combined cycle generation. Despite this three of the five OECD countries and four of six non-OECD countries which provided cost data using their own discount rate still project nuclear power to be the cheapest source for base load electricity generation from plants to be commissioning by the turn of the century.

Cost comparisons based upon a 5% per annum real discount rate in all countries, indicate that nuclear power would be the cheapest option in thirteen of the fifteen countries covered in the study. Exceptions were regions with direct access to cheap coal, e.g., northwest China, western USA and western Canada or gas, e.g., United Kingdom and the Netherlands where nuclear and coal generation cost projections are similar. At a 10% discount rate, nuclear power remains the cheapest option in only five of the countries surveyed (see Figure 1).

This sensitivity to discount rates arises directly from their effects on investment costs, which are higher for nuclear power plants than for fossil fuelled power plants. Figure 1 illustrate detailed comparisons between nuclear, coal and gas generated electricity resulting from the last OECD study [37].

There is no indication of any imminent technological breakthrough which might reduce significantly nuclear electricity generation costs nor the costs of classic thermal electricity generation. However, standardisation, consistent planning and project management, and collocation may improve the economic performance of power plants in a number of countries. In the case of capital intensive nuclear projects, improvements could be achieved through the implementation of more stable and coherent regulatory and licensing regimes leading to shorter construction lead times and reducing the financial risks. Apart from this the electricity generation costs are expected to remain broadly stable unless there are major fuel price, regulatory or fiscal changes.

## 7.2. EXTERNAL COSTS

External costs arise from detrimental economic consequences from activities, such as electricity generation, that accrue to society but that are not accounted for in the direct cost calculations, and, therefore, are generally not fully reflected in the decision making process for selecting a given technological option. It should be stressed that some benefits, as opposed to costs, also arise from electricity generation options which are not captured by classic economic assessments.

In the electricity sector, decisions used to be based upon least cost planning, costs being evaluated on the ground of the economic rules prevailing in a given country and applicable to the utility responsible for the system expansion planning and implementation. As mentioned above, in the case of nuclear power the levelised cost already takes into account most of the potential impacts to society from the entire energy chain from mining through electricity generation to decommissioning of power plants and fuel cycle facilities, and waste disposal. However, the levelised costs given in Section 7.1 do not incorporate the full impacts of electricity generation options on the economy and society at large. Some studies are now attempting to quantify "external" or "social" costs of electricity generation in order to incorporate them into the economic comparison of different options.

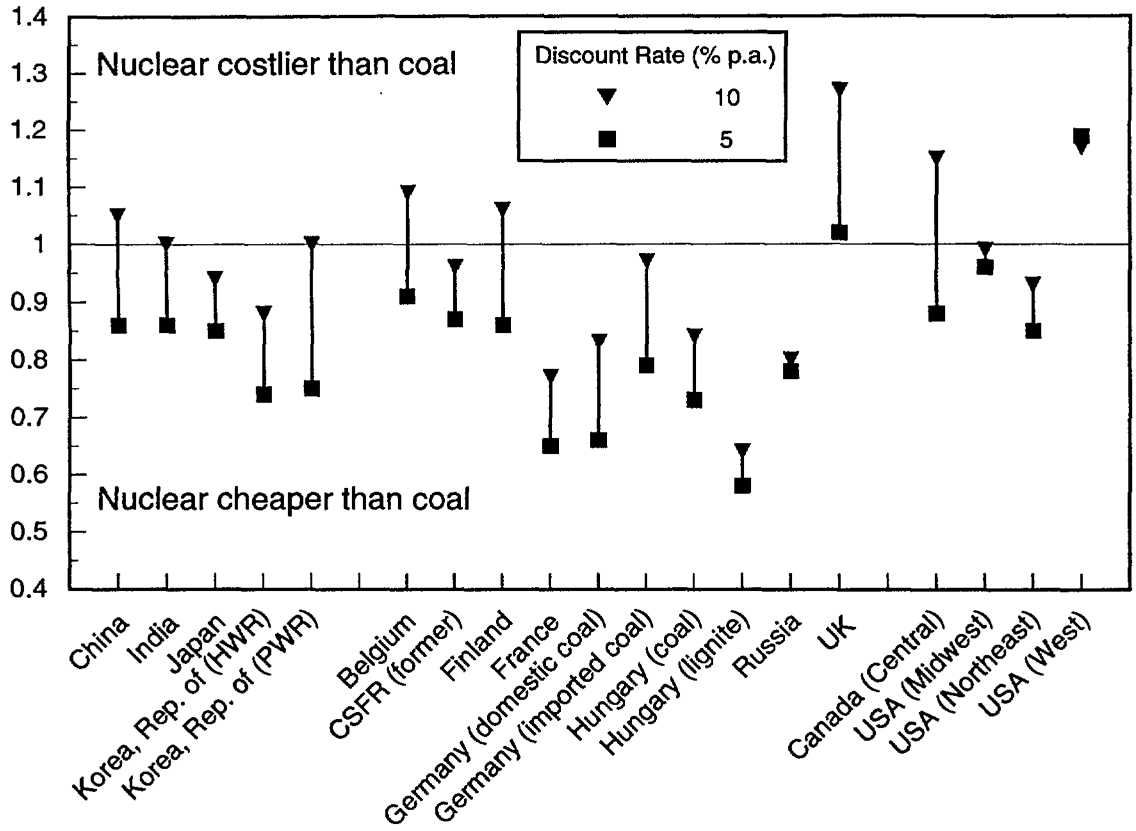


*FIG. 1(a). Generation cost ratios (nuclear/coal).*

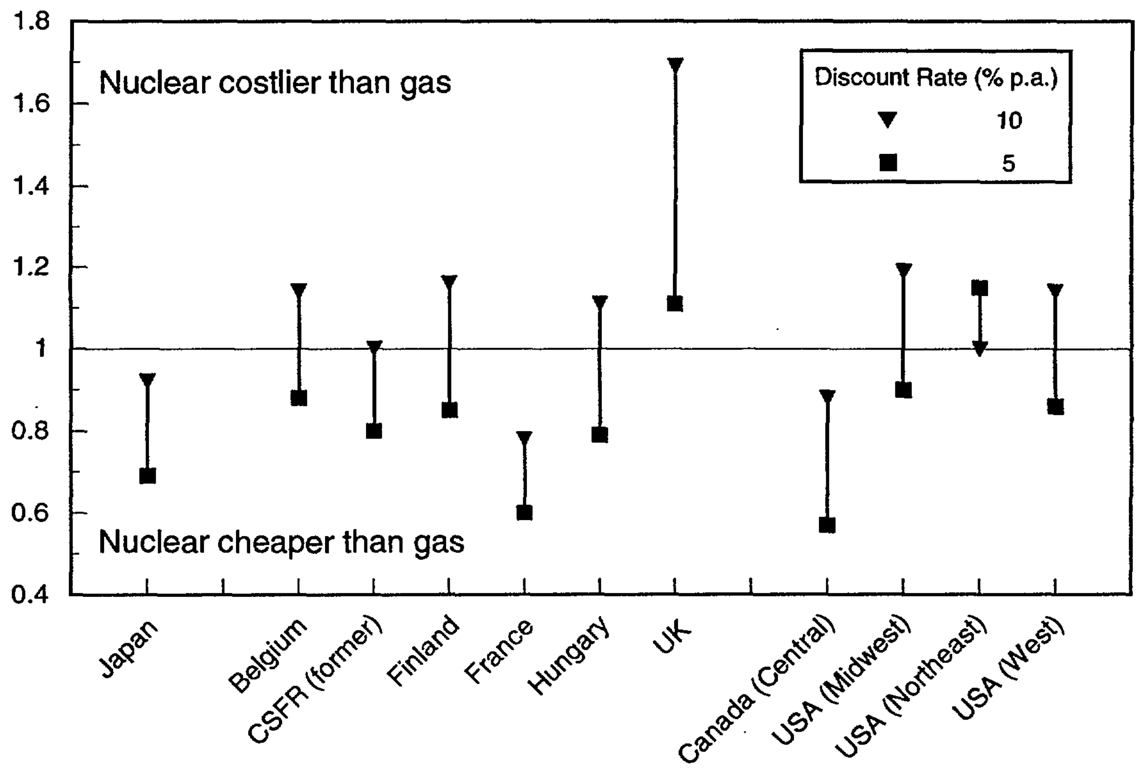


*FIG. 1(b). Generation cost ratios (nuclear/gas).*

Health and environmental externalities are treated in Section 8. The present section, which is based upon an OECD/NEA study on "Broad economic impacts of nuclear power" published in 1992 [38], deals with other social costs as listed in Table II.

TABLE II. BROAD ECONOMIC IMPACTS OF NUCLEAR POWER

| Primary impact | Economic consequences |
|---|---|
| **(a) Economic** | |
| Direct cost savings<br>Fossil fuel price capping<br>Energy supply security (Avoided lost output)<br>Avoided net fuel imports<br>Enhanced technology exports<br>Electricity price stability<br>Intellectual capital gains | Enhanced productivity<br>Improved competitiveness<br>Improved terms of trade<br>Currency appreciation<br>and enhanced economic growth |
| **(b) Social** | |
| Changed employment levels<br>Changed risk perceptions (weapons, accidents, health, gene pool)<br>Changed social consensus<br>Changed cultural impact<br>Changed ecological impacts | Some direct effects on resources<br>Changed institutional costs<br>Changed economic efficiency |

Among the social costs of electricity generation systems, some can be quantified and valued with a reasonable degree of certainty while some can only be characterised in a qualitative way. The broad economic impacts which are not captured fully by the levelised cost calculation method but can be quantified are mainly the secondary effects of investments in nuclear projects at the national and local levels, the induced employment, the impacts of nuclear power development on the balance of payment, and the macroeconomic impacts of nuclear programmes on energy price stability. The impacts of more qualitative nature include security of energy supply, natural resource depletion, technological progress resulting from spin-off effects and socio-cultural induced effects.

The secondary impacts of investments arise from the creation of additional economic activity beyond what is reflected in the microeconomic levelised cost analysis. The multiplier effect due to the use of incomes from economic actors involved in nuclear projects, or any other project, in buying goods and services or investing in other projects, can be captured by input-output analysis or similar studies. The resulting increase in regional or national income may exceed the direct investment cost by a significant margin and local impacts are generally larger in relative terms. Input-output studies have indicated that in the case of Japan the multiplier for nuclear investments exceeds two.

The nuclear industry is a significant employer, with a contribution up to a few percent of the working population, in countries where nuclear power has been broadly deployed. One characteristic of this industry is its relatively high proportion of skilled and graduate staff relative to most other major energy and manufacturing industries. However, nuclear power is less labour intensive than electricity generation chains using coal and renewable sources. This fact may be an incentive to pursue other options than nuclear power in countries where high employment is a social objective. However, least cost electricity generation systems provide economic competitiveness of the country which in turn increase the manpower requirements. Therefore the development of manpower intensive electricity generation alternatives for social reasons might be counter-productive in the long term. Also, studies that have sought to establish the quantitative implications of nuclear power have suggested that medium term employment losses following its abandonment would arise directly from the consequences of higher electricity prices.

The effect of electricity generation choices on the balance of payment is often considered as a major issue by policy makers on the basis that anything that reduces imports and/or increases exports is beneficial to the national economy. The nuclear industry can affect trade balances through the import or export of technology and fuels. Its potential for technology export has been advanced as an argument in many countries in support of its development, while its ability to substitute low cost uranium imports for high cost oil, coal or gas has also been argued in favour of its adoption.

The deployment of nuclear power on a large scale as a substitute for fossil fuels has alleviated the pressure on oil, gas and coal markets, and contributed to primary energy source price stability. This benefits all fuel users even though they themselves may not have implemented nuclear programmes. In particular, the substitution of nuclear power plants to fossil fired power plants in industrialised countries has allowed developing countries to benefit from cheaper fossil fuels.

Security of supply is a key element of sustainable electricity system expansion strategies. The enhancement in this regard provided by nuclear power development is highly country specific. The choice of any supply option relying on indigenous sources, i.e., domestic fuels or renewable sources, or requiring small quantities of imported fuel, like nuclear power, reduces the dependence on external fuel sources, the supply of which may be disrupted by political or economic events occurring outside of the country. In practice, security of supply may be ensured, especially for imported fuels, by the establishment and maintenance of strategic stockpiles. With regard to nuclear fuel, inventories covering several years of power plant consumption can be maintained at the reactor site since the volumes are small. Moreover, the cost of purchasing and holding fuel stockpiles is much smaller for nuclear power plants than for coal, oil or gas fired power plants.

Few attempts have been made to tackle the question of economic impact of resource depletion in terms of eroding the country's "natural capital". In the case of uranium, since nuclear power is the only foreseeable use of this resource, the long term impact on sustainability of depleting resources is likely to be negligible. Moreover, presently known uranium resources alone could provide all the world's energy requirements for centuries if breeder reactors were to be deployed.

The development of advanced technologies calls for new materials, techniques and skills that can find application in other sectors of the economy with consequent economic benefit. Nuclear power has contributed to substantial progress in fields as diverse as: medicine and health; industrial processes and their control; environmental science, monitoring and control; agriculture; and mineral exploration and extraction. The range of spin-off benefits of nuclear power is wide and is not readily susceptible to quantitative analysis. While the spin-off benefits from past investments in nuclear development have no direct relevance for the future, the development and deployment of advanced reactors and nuclear fuel cycle facilities is likely to provide similar benefits. However, alternative options, especially renewable electricity generation chains would be likely to have different but equally beneficial spin-off effects.

Nuclear power has provided a focus for opposition to advanced technology, to centralisation of decision-making and to other features of modern industrial society. As such it has contributed to a significant loss of social consensus and a degree of social conflict in many countries and this has imposed extra costs on society as a whole. It may be that some other focus for this opposition would have been found if nuclear power had not been developed. The costs of public information, institutional and physical measures taken for assuring the public that their interest and safety are being protected, and programmes that have been abandoned due to public opposition could be regarded as negative spin-off effects. It is doubtful whether countries which will initiate or continue nuclear programmes will experience significant extra costs of this nature as a result of these programmes.

The analysis carried out by NEA [38] concluded that the non-environmental externalities of nuclear power do not yield costs or benefits that will significantly impact on its competitiveness. The non-environmental external costs were estimated to fall within the range of uncertainty surrounding the standard projected levelised cost of electricity generation.

# 8. HEALTH AND ENVIRONMENTAL ISSUES

Health and environmental impacts of nuclear power mainly arise from releases of radioactive materials. The other emissions, residuals and burdens from nuclear power plants and fuel cycle facilities are generally much lower than those from alternative electricity generation chains. Concerns regarding radiological impacts focus mainly on the effects of low probability/high consequence severe accidents and final disposal of radioactive wastes. The results from comparative assessment studies of different energy systems for electricity generation indicate that, under routine operation conditions, nuclear power and renewable energy systems tend to be in the lower spectrum of risk and that energy systems based on coal and oil are in the higher spectrum. Rough estimates suggest that the human health risks from severe accidents from nuclear, oil and natural gas chains are of the same order of magnitude and two order of magnitude smaller than those from hydroelectric systems [39].

It is now widely recognised that all stages of the energy chain should be considered in the comparative health and environmental impact assessment of different electricity generation options. However, the approach adopted in the nuclear sector to limit, control and mitigate potential health and environmental impacts from nuclear facilities is the most comprehensive and has tackled life cycle issues from the start of the use of the technology. In this connection, two specific methodologies were developed and used for assessing and controlling the potential impacts of nuclear power systems, i.e., the "as low as reasonably achievable" (ALARA) principle for routine operation and the use of "probabilistic risk assessment" (PRA) for severe accident risk assessment.

The rules for limiting radioactive emissions were developed several decades ago when environmental protection was regarded as essentially protection of the environment in order to protect man. Mammals are significantly more vulnerable to radiological effects than many other types of animals or plants as radioisotopes tend to concentrate in the food chain. Humans being at the top of this chain is the most vulnerable species. The general principles currently applied in most countries are those set out by the International Commission on Radiological Protection (ICRP) in 1977 [40] and revised subsequently according to the progress in scientific knowledge [41]. In particular, "The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk". Therefore, radiation protection limits set up to protect humans more than satisfy general health of living creatures and environment protection.

The recommendations of ICRP are based upon two principles: emissions should be kept below a level which can impact human health or the environment; and emissions should be reduced below the limits authorised whenever the cost of achieving the reduction is lower than the estimated benefit of the corresponding impact reduction. In practice, the nuclear industry has usually adopted more stringent standards than the authorised limits and even than the level corresponding to the optimum of cost-benefit analysis.

This covers the impact from normal operation which are detailed in Section 8.1, but abnormal operation must also be taken into account. This risk must be calculated and to do this, the PRA (probabilistic risk assessment) methodology was developed. This consists of using a top-down approach: first determining the failure, such as a large off-site release, and then all the causes leading to that failure. These causes are related to each other and quantified. The quantification is essentially based on historical failure data. PRA therefore provides a comprehensive structured approach to identifying failure scenarios and provides a mathematical tool for deriving numerical estimates of risks. PRA exposes the safety assumptions to peer review, and permits drawing comparisons between risks in different technologies and of setting rational standards. PRA is intended: to identify the dominant risk contributors, to help in comparing the options for reducing risks such as redesign or testing schedules, to identify problems and quantify these within a degree of magnitude.

The potential health impacts of radioactive emissions from nuclear power plants and fuel cycle facilities can be assessed by the dose released which are monitored by the United Nations Scientific

Committee on the Effects of Atomic Radiation (UNSCEAR). The last report of this Committee [42] states that the collective effective dose committed to the world population by a 50-year period of operation of nuclear power facilities, i.e., power plants and nuclear fuel cycle facilities including uranium mining, is 2 million man· Sv, as compared to 650 million man· Sv committed by natural radiation and 165 million man· Sv committed by medical diagnosis and treatment exposure.

## 8.1. EMISSIONS AND RESIDUALS DURING ROUTINE OPERATION

This section deals with emissions and residuals from the entire fuel chain from fuel extraction through electricity generation to waste management and disposal. which are put into perspective with the emissions and residuals from alternative options. Some emphasis is given to greenhouse gases since this is the focal issue as far as IPCC is concerned.

### 8.1.1. Greenhouse gases

Nuclear power can be considered a major option for greenhouse gas emission reduction. It contributes only to a very small extent to the global emissions of greenhouse gases due to the use of fossil fuels in the extraction and processing of uranium, to the electricity used in uranium enrichment, when this electricity is generated by fossil fuelled systems, and to fuels used in the production of steel and cement for reactor and fuel cycle facilities construction. These contributions are negligible relative to those from the direct use of fossil fuels for electricity supply. Since the main source of greenhouse gas emissions within the nuclear chain is the electricity used at the enrichment step, the introduction of the centrifuge and laser processes, which are less electricity intensive than the gaseous diffusion process, and/or the use of nuclear power or renewable sources for supplying electricity to enrichment plants can reduce even further the emissions of greenhouse gases from nuclear power.

Taking into account the entire up-stream and down-stream energy chains for electricity generation, nuclear power emits 40 to 100 times less carbon dioxide than currently used fossil fuelled chains [43]. In general the greenhouse gas emissions from the nuclear power chains are comparable to those from renewable energy sources used for electricity generation and from energy conservation measures requiring the use of materials for reducing the specific electricity demand for supplying the same end-use service [44, 45]. Table III gives average carbon dioxide emissions corresponding to various technologies for equivalent end-use service.

In 1993, the reduction of carbon dioxide emissions resulting from the use of nuclear power was about 2100 Mt, or some 7% of the total emissions from the energy sector, as compared to a coal based electricity generation system. Countries which implemented large nuclear programmes in the period from 1965 to 1990 such as Belgium, France and Sweden, improved significantly the benignancy of their energy strategies, reducing their carbon dioxide emission factors by one or more Tg of carbon dioxide per EJ per year [47].

If nuclear power was being used to provide 70% of an estimated OECD electricity demand of 12 000 TW· h by 2030, the avoidance of carbon dioxide emissions would amount to about 1.2 Gt of carbon annually at the end of the period as compared to using coal at 50% efficiency. In its last "20-year European Energy Forecast" the US research agency DRI foresees a rise by 11% per year of carbon dioxide emissions in Europe after the turn of the century due to the replacement of nuclear units by coal and gas fired power plants [48].

### 8.1.2. Other emissions and residuals

Nuclear power plants and fuel cycle facilities are also practically free from atmospheric emissions such as sulphur dioxide, nitrogen oxides, dust and particulates. In France, where nuclear power has expanded to provide three-quarters of the electricity produced, the emissions of sulphur dioxide from the electricity sector dropped by a factor of 10 and the emissions of dust by a factor of almost 40 [49]. However, nuclear facilities emit small amounts of radioactive gases in the atmosphere and solid radioactive wastes arise which have to be disposed of safely. In general the radiological impacts on the public associated with nuclear power are comparable or lower in this regard to those associated with other alternative power generation and equivalent energy conservation measures requiring the use of materials to achieve their effect, such as loft insulation and cavity wall insulation. Other environmental burdens from nuclear power plants and fuel cycle facilities, such as land and water use are not greater than those of alternative options for electricity generation.

TABLE III. CARBON DIOXIDE EMISSIONS FOR VARIOUS TECHNOLOGIES [46]

| **Technology** | **Average total emissions** (100 000 tonnes of carbon dioxide per 5 TW·h of electrical energy saved/generated) |
|---|---|
| **Generation options** | |
| Coal-fired (1) | 59.1 |
| PWR (2) | 2.3 |
| PWR (3) | 0.4 |
| PWR (self-supplied) (4) | 0.2 |
| FBR | 0.2 |
| Hydro power | 0.9 |
| Wind power | 0.5 |
| Tidal power | 0.5 |
| **Efficiency measures** (5) | |
| Roof insulation (10 inch fibre glass) | 0.2 |
| Cavity wall insulation (polystyrene foam) | 0.2 |
| Low-energy lighting | 0.2 |

(1) Pulverised fuel plant.
(2) Using diffusion enrichment (USA).
(3) Using centrifuge enrichment (Europe).
(4) Using nuclear electricity to power enrichment plants.
(5) Emissions in product manufacturing.

In routine operation nuclear reactors produce highly radioactive fission products and actinides in the fuel, which are fully contained within the fuel rods for the vast majority of fuel elements [50], as well as activation products formed by neutron irradiation of reactor components. Small quantities of radioactive materials are released to the environment during reactor operation and at fuel production and spent fuel management plants.

These releases and direct exposures to radiation are carefully monitored and controlled to levels believed to cause insignificant environmental and biological damage on the basis of recommendations by the independent International Commission on Radiological Protection (ICRP) as interpreted by national governments and agencies. Apart from meeting the regulatory requirements set out by these agencies the owner and operator on a nuclear facility must obey the ALARA principle. Results from measurements show that the average doses received by workers in nuclear facilities are about equal to or lower than that received from the natural background radiation.

In this connection, it may be pointed out that the nuclear industry in OECD countries are spending sums on the reduction of radiation exposures of workers and the public which, if spent in other sectors of the economy, would yield greater numbers of avoided premature deaths or other commensurate social benefits. For example, in the case of the United Kingdom [51], modifications to the Sellafield plant liquid effluent treatment facilities in the 1980s corresponded to an implicit valuation of life in excess of £ 10 million.

Nevertheless, the emissions result in some exposure of the workers and much smaller exposure of larger numbers of the general public. This results in a very small risk of severe somatic effects possibly leading to premature death in both groups, together with the possibility of some genetic damage that might be passed to future generations. The ICRP publishes its assessments of the risks of premature death and genetic damage as a function of radiation dose on the basis of linear extrapolation towards low doses from the observed effects of radiation on populations that have, in the past, received doses sufficiently high to produce statistically observable effects, such as atom bomb survivors and radium paint workers, as well as from experimental observations on animals [52, 53].

Combining these risk estimates with the measurable or calculated exposures of workers and the public to the routine emissions from nuclear power plants and fuel cycle facilities, it is possible to estimate the overall effect of civil nuclear applications. These exposures amount on average to less than 0.1% of the public's exposure to radiation from naturally occurring radioactivity, which arises from radioactive minerals contained in the ground, atmospheric radon and cosmic rays.

The calculated incidence of premature deaths arising from routine nuclear power generation and the nuclear fuel cycle is smaller than that from coal and oil production and use, both in absolute terms and expressed per unit of electricity produced, as shown in Table IV (a) [54]. The values of radiation effects are calculated because induced cancers and other severe health effects are too low to be detectable with any statistical significance against the background of the same effects due to causes other than radiation. The values given in the table refer to quantitative assessment of immediate and delayed fatalities arising from normal operation of power plants and their associated fuel chains. They include both conventional accidents during mining, transportation and construction of power plants and fuel chain facilities, and radiation effects but exclude nuclear accidents, which are discussed in Section 8.2.

Table IV (b) shows the main results from a study carried out in 1982 [55] covering non-fatal accidents and disease hazards due to electricity generation, which exceed the fatalities by a considerable margin. The figures given in the table should be considered as indicative since scientific views on the health impacts from fossil fuel combustion are still diverging. However, according the study, non fatal accidents and diseases resulting from electricity generation are generally higher for fossil fuelled chains than for the nuclear chain.

Concerns have been expressed as to the potential increases in cancer among populations living near nuclear facilities. It had been suggested by some investigations carried out in the United Kingdom [56] that diseases such as childhood leukaemia, would occur more frequently among the population living close to nuclear facilities or in the families of nuclear workers than in average. However, these observations have been refuted in a paper published in "Nature" in 1994 [57], which concludes that paternal exposure is not to blame for childhood cancers. A study on 75000 radiation workers in the UK, performed by experts from the Imperial Cancer Research Campaign and from medical departments at Oxford and London Universities, shows that, in so far as data are available for leukaemia incidence in relation to dose received, they do not call into question the currently adopted radiation protection standards [58, 59]. Studies carried out in other countries, such as Canada, France and the USA [60–63], are leading to the same conclusions. Furthermore, the 1994 UNSCEAR Report (see Ref. [42]) states that "none of the increases of leukaemia and non-Hodgkin's lymphoma reported in the vicinity of nuclear installations seems likely to have been caused by environmental exposure to discharges of radioactive materials, nor can any of them be accounted for by paternal exposure to radiation at work before the affected young people were conceived".

TABLE IV (a). SUMMARY OF FATALITY RATES FOR DIFFERENT ENERGY SYSTEMS (fatalities/GW(e)· year)

| Energy system | Occupational | | Public | |
|---|---|---|---|---|
| | Immediate | Delayed | Immediate (a) | Delayed |
| Coal | 0.4-3.2 (b)<br>0.16-1.7 (e) | 0.13-1.1 (c)<br>0.02-0.15 (f) | 0.1-1.0 | 2.0-6.0 (d) |
| Oil | 0.20-0.85 (g)<br>0.22-1.35 (h) | | 0.001-0.1 | 2.0-6.0 (d) |
| Gas | 0.10-5 (g)<br>0.17-1.0 (h) | | 0.2 | 0.004-0.2 (d) |
| Nuclear (LWR) | 0.09-0.5 (b)<br>0.07-0.4 (e) | 0.13-0.37 (b)<br>0.07-0.33 (e) | 0.001-0.01 | 0.005-0.2 |

Note: Unless otherwise specified, the total for the conventional thermal systems includes extraction, processing, fuel transportation, construction and operation of the power plant; the total for nuclear includes extraction, ore processing, conversion, enrichment, fabrication of fuel elements, fuel transportation, construction and operation of the power plant, fuel reprocessing and waste disposal. The risk from severe accidents is not included.

(a) applies to transport, being the major contributor to risk;
(b) applies to underground mining conditions;
(c) applies to underground mining, being the major contributor to risk;
(d) applies to power plant operation, being the major contributor to risk;
(e) applies to surface mining conditions;
(f) applies to surface mining, being the major contributor to risk;
(g) applies to land extraction;
(h) applies to offshore extraction.

TABLE IV (b). NON-FATAL ACCIDENTS AND DISEASE HAZARDS PER GW(e)· YEAR

| Energy system | Accidents | | Diseases | |
|---|---|---|---|---|
| | Workers | Public | Workers | Public |
| Coal | 60 | 18 | 3 | 2000 |
| Oil | 30 | ? | ? | 2000 |
| Natural gas | 15 | 0.005 | 0 | 0 |
| Nuclear | 15 | 0.1 | 0.1 | 16 |

In Germany, an evaluation of the cost of the overall health and environmental costs of a number of generation options including nuclear power have concluded that the health effects resulting from normal operation of nuclear power plants amount to less than 0.8% of the total generation cost for nuclear power [64].

### 8.1.3. Solid wastes

As indicated in Section 6.3, the volumes of radioactive wastes arising from nuclear power plants and fuel cycle facilities are small and there is a wide scientific and technical consensus that the necessary long term exclusion of these wastes from the biosphere can be achieved. The goals and criteria applied for radioactive waste management are those set up for all nuclear activities and facilities. Their objective is to protect the present population as well as future generations and the environment.

Radioactive wastes are collected, processed and conditioned according to their category, i.e., LLW (low level waste), ILW (intermediate level waste) and HLW (high level waste). Finally, wastes conditioned and packaged so as to conform with national requirement are disposed of. Non-radioactive toxic chemicals contained in radioactive wastes are either destroyed or immobilised within the treatment processes. The approaches adopted at all stages from waste collection to final disposal are in line with the ALARA principle. The protection goals used in radioactive waste management apply in the first instance to “critical” groups which could be exposed more the average population as well as to future generations in order to make sure that the latter are not exposed more than the present one to radiation resulting from the waste generated today. Since humans appear to be one of the categories most sensitive to radiation, protection measures designed for protecting humans more than satisfy general environmental protection principles.

Concerns are raised by the long term perspective which has to be considered when implementing repositories for long lived radioactive waste. However, this long term perspective is nor unique to nuclear wastes. Although chemical wastes do not seem to cause similar concerns, they may be equally or more hazardous over even longer time spans.

## 8.2. RISKS DUE TO ABNORMAL OPERATION

The perceived risk of severe nuclear accident is a key factor in the public opinion towards nuclear power. Such an accident would result in the release of a significant fraction of the fission products, which are normally held within the reactor core, into the atmosphere and entail major impacts on human health and the environment. The public perception of nuclear risks is linked with knowledge of the awesome consequences of atomic weapons explosions, despite the assurances given by the civil nuclear industry that nuclear power plants can not explode like atom bombs. The risks of nuclear accidents are comparable with, and in the OECD much lower than, risks for other human activities. The Senior Expert Symposium on Electricity and Environment (see Ref. [39]) concluded that "the human health risks from severe accidents from nuclear, oil and natural gas are of the same order of magnitude and two orders of magnitude smaller than those from the hydroelectric option" although such comparisons should be “interpreted with great caution”.

The accident at Three Mile Island in the USA and other less severe incidents have demonstrated the ability of the shut-down and containment systems of modern reactors in OECD countries to avert potential hazards. The Chernobyl accident in the former Soviet Union, on the other hand, released a significant part of the fission products from the reactor’s core and had severe environmental and health impacts. However, this accident arose from a series of design and management blunders that were precluded in other reactor types by the criteria laid down for plant design, construction and operation. The consequences of the Chernobyl accident on public opinion towards nuclear power were dramatic worldwide. Its health and environmental impacts have been analysed and continue to be studied [65–67].

Stringent safety standards and regulations have been set up in most countries where nuclear power plants and fuel cycle facilities are operated. The US Nuclear Regulatory Commission, for example, issued in June 1986 a policy statement on safety goals for the operation of nuclear power plant. Their qualitative safety goals were: "Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health. Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risk."

Quantitative objectives were to be used in determining achievement of the above safety goals. These were that: "The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed 0.1% of the sum of prompt fatality risks resulting from other accidents to which members of the US population are generally exposed. The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed 0.1% of the sum of cancer fatality risks resulting from all other causes."

The risks of a major core-release accident in modern water cooled reactor designs are estimated by systematic risk assessment analyses. There is a small probability that a major accident could occur and a proportion of these accidents could release significant radioactivity to the environment. The probability varies with reactor design and circumstances but is generally regarded to be very low. The first major study based upon probabilistic risk assessment was the Rasmussen report, published by the US Nuclear Regulatory Commission (USNRC) in 1975 [68]. The study concluded that the risks from one hundred US LWRs was small as compared with other individual or societal risks. The Rasmussen study was reviewed by Lewis [69] and EPRI [70] some years later. Both concluded that, although it failed to attach sufficient weight to the uncertainty in the probability estimates, the methodology was sound.

In the UK, the design target is that the overall probability of a core melt from all causes should be below one in 1 million per reactor per year [71, 72], which is lower than some studies have suggested for existing reactors. Subsequent studies by the Federal Ministry of Research and Technology of the Federal Republic of Germany [73, 74] and the USNRC Regulatory Commission (NUREG 1150) have confirmed the general conclusion that the risks from LWRs are low. One recent study for the Dutch Government [75] has concluded that the probability of core melt accidents in future LWRs will be as low as one in 10 million to one in 100 million per year.

The consequences from radioactive releases after the TMI accident have been thoroughly analysed. The Pennsylvania State University Medical Centre has made a study of the total radiation dose, since the TMI plant (2 units) started operation in 1978, received by the entire population living within 50 miles (80 km) of the plant. Results recently published by the USA Nuclear Industry Institute [76] show that the total accumulated dose, from both normal operation and the TMI-2 accident, to the entire population is only about 10 to 30 man· rem; by comparison, the accumulated dose from natural background radiation amounts to more than 250 000 man· rem. When expressed as an average dose per person, the total accumulated dose due to the TMI plant is about 8 millirem per person (equivalent to one chest X ray), while the natural background dose per person is about 300 millirem per year (equivalent to 1.5 times the dose from a head CAT scan). That is, each person would receive each year about 40 times as much dose as the entire exposure accumulated since 1978 from the TMI plant.

In economic terms, the financial risk associated with low probability/high consequence nuclear accidents is very low. The negotiated settlement for off-site costs arising from the Three Mile Island accident was just over US $26 million [77]. The off-site costs associated to the Chernobyl accident were officially estimated by the Soviet Government to be US $8000 million but some estimations reached US $200 000 million. Assuming the higher cost estimation, i.e., US $200 000 million, and a frequency of accident of $10^{-5}$, while the standard in most countries is lower than $10^{-6}$, the annual cost associated with the risk of severe accident would be US $2 million for a typical nuclear unit as compared to an annual electricity generation cost of some US $200 million for the same unit. Therefore, statistically the financial risks associated with low probability accidents is below 1% and probably below 0.1% of the generation cost. In practice governments have been prepared to give international guarantees concerning compensation for major incidents, though the reactor owners must procure private insurance which covers a substantial portion of the risk. Similar guarantees are generally not in place for other electricity generation systems or industrial complexes which have the same or higher degree of risks.

## 9. CONCLUDING REMARKS

Population growth and economic and social development will require additional electricity generation capacities, especially in developing countries. New technologies will have to be competitive and environmentally benign. Nuclear power is one of the technological options that can provide electricity at relatively low cost and with low health and environmental impacts.

Nuclear power programmes have slowed down in many countries over recent years owing to a number of reasons, including concerns of the public regarding nuclear safety and radioactive waste disposal. However, in some countries nuclear programmes continue to be implemented. The safety and economic performance of nuclear power plants are very satisfactory in most countries and are improving steadily. The nuclear industry is showing a commitment to providing new technology to meet the increasing demands of competitiveness and public acceptance. Clearly the incentives for further deployment of nuclear power are strong and, if the objectives of advanced nuclear power development programmes are met, nuclear power could provide a long term, safe and economical energy supply.

The fact that reactor improvements can be made in future applications does not reflect adversely on present operating systems. It is typical of any advancing technology that experience identified opportunities for improvement, but this does not mean that the current technology is unsatisfactory or obsolete. The desire to further reduce the residual risk of future reactor operations, for example, does not indicate that the current generation of nuclear power plants is not safe enough. Rather, some hard-won knowledge has been gained. This knowledge should be a foundation for further reduction of residual risk, and further protection of the utility investment in nuclear plants.

A range of electricity generation technologies, based on fossil fuel burning, renewable energy sources and nuclear power, is available or under development. Factors that will influence strategies for electricity system expansion include economics, security of supply and health and environmental impacts. The increasing awareness of potential health and environmental impacts of human activities has already induced the development of cleaner and more efficient technologies. The implementation of abatement devices and the increase of efficiency of power plants have substantially reduced the emissions and other residuals from fossil fuel chains. Nevertheless, sustainability, and in particular significant reductions of greenhouse gas emissions, can only be achieved by a broader deployment of non-fossil energy sources for electricity generation. Most renewable energy sources other than hydropower still require considerable research and development effort before they will be ready for large scale deployment and economically competitive for base load electricity generation. Therefore, nuclear power is considered by many experts as being the most likely non-fossil energy source, which can be deployed on a significantly larger scale, for implementing electricity supply strategies aiming towards sustainability and competitiveness.

A broad range of factors will influence nuclear prospects in the medium and long term. Technologies for reactors and fuel cycle facilities, as well as fuel resources, are available to sustain a large scale deployment of nuclear power worldwide. The barriers to nuclear power development are more institutional and organisational than technological. The main prerequisites to a revival of nuclear power are the alleviation of public concerns regarding safety, waste management, and the risk of proliferation of nuclear weapons. In some developing countries, where the need for electricity is the most important, nuclear power is a viable option. However, a prerequisite for the implementation of nuclear programmes in these countries is the establishment of adequate mechanisms for technology adaptation and transfer as well as financing.

The nuclear power plants of the present generation ensure already a high level of safety based upon built-in redundancy and relying on decades of experience with proven technology and engineering. Advanced reactors are being designed and developed with new approaches to address the challenge of increasingly demanding safety requirements by, inter-alia, utilising more passive safety systems in order to reduce the probabilistic risk of accidents and to achieve very low on-site and off-site impacts in the event of a potential accident. Furthermore, consensus on international practices and standards for nuclear safety is emerging. The International Nuclear Safety Convention, signed by more than fifty States as of January 1995, covers nuclear power reactors and establishes agreed benchmarks together with a peer review process for ensuring a high level of safety everywhere in the world.

Technical options for conditioning and final disposal of high level waste have been tested in underground laboratories. The tests have aimed towards validating the models used in assessing the safety of the proposed repositories, and their costs. The implementation of high level waste repositories, which is planned for early in the next century by several countries, will demonstrate the ability to handle the issue with a satisfactory level of safety for both current and future generations. All these positive elements should enhance the public acceptance of nuclear power and facilitate its broader deployment.

The cost of electricity generation will remain a cornerstone for the assessment and choice of options in electricity system expansion strategies. Recent studies show that in many countries nuclear power is among the cheapest sources for base load electricity generation, especially where solid mineral fuels are not accessible at low production costs. Designers of advanced nuclear power plants are aiming towards reducing capital costs through streamlining the reactor systems and reducing the amount of material required for the construction. Investment costs will also be reduced by shortening construction lead times through using more components that could be prefabricated off-site. Depletion of non renewable natural resources and the enforcement of more stringent atmospheric pollution standards are likely to raise the cost of electricity generated by fossil fuel power plants, thereby making nuclear power even more attractive economically. Financing the high capital costs of nuclear power plants will remain a key issue in many developing countries which are contemplating the implementation of nuclear programmes. The implementation of new financing approaches with support from development banks would facilitate the development of nuclear power in these countries.

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