PROSPECTS FOR NUCLEAR ENERGY IN THE 21ST CENTURY AND THE ROLE OF THE INTERNATIONAL ATOMIC ENERGY AGENCY

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ABSTRACT

In the second half of the 20th century nuclear power has evolved to an industry that supplies 17% of the world's electricity. A great deal has been achieved and many lessons have been learned. The past decade, however, has seen stagnation or slow growth in nuclear power plant construction except in East Asia. The turn of the century can be a turning point for nuclear power due to increasing world energy consumption, the need to reduce greenhouse gas emissions, and improvements in operation and economics of nuclear power plants. Advanced reactor designs are being developed so that the technology will be ready for the next century. Issues that have dampened support for nuclear power are being addressed through the emerging global nuclear safety culture, attention to nuclear waste disposal and a strengthened safeguards system. The International Atomic Energy Agency promotes technical information exchange and co-operation, provides a source of balanced, objective information, and publishes reports on the current status of reactor development. The Agency will continue to play a major role as the nuclear industry faces the challenges and opportunities of the 21st century.

INTRODUCTION

In the second half of the 20th century nuclear power has evolved from the research and development environment to an industry that supplies 17% of the world's electricity. In these 50 years of nuclear development a great deal has been achieved and many lessons have been learned. By the end of 1997, over eight thousand five hundred reactor-years of operating experience had been accumulated.

The past decade, however, has seen stagnation in nuclear power plant construction in the Western industrialized world, slow nuclear growth in Eastern Europe and expansion only in East Asia. The prospects for nuclear energy have been affected by a number of factors: economic slowdowns and general reductions in the rate of increase in energy demand, coupled with oversupply in some countries; the Chernobyl accident with its effect on public confidence in nuclear power; slow progress in properly implementing nuclear waste disposal; difficulties, for utilities in some countries, in transforming from a rapidly growing industry to routine operation of ageing facilities, resulting in management, performance and bottom-line problems; electricity supply deregulation; and the increased competition from natural gas.

The turn of the century has the potential to be a turning point for nuclear power because of: (a) fundamentally solid future prospects resulting from increasing world energy consumption, nuclear power's contribution to reducing greenhouse gas emissions, nuclear fuel resource sustainability, and improvements in operation of current nuclear power plants; (b) advanced reactor designs that will improve economics and availability, and further enhance safety; and (c) continued attention to the key issues of nuclear safety, nuclear waste disposal and non-proliferation of nuclear weapons. These three topics, and the role of the IAEA in addressing them, are discussed in the following sections.

FUTURE PROSPECTS

Nuclear power operates in a growing market segment [1]. The substantial increase in global energy consumption in the coming decades will be driven principally by the economic growth and industrialization of developing countries, whose three quarters of the world's inhabitants consume only one quarter of the global energy. North America has a per capita consumption more than twice that of Europe and almost eight times greater than that of South East Asia and the Far East [2]. Strong economic growth in many developing countries is already leading to sharp increases in per capita energy consumption. Consumption will continue to rise, driven also by the projected two-fold expansion in world population during the 21st century that will occur overwhelmingly in the developing regions [3].

A 1995 study carried out by the World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA) [4] considered three global energy scenarios for the next century: a high, middle and low economic growth scenario. The study projects by mid-century a range of energy demand increase from about 50% for the low economic growth case to an increase of more than 150% for the high growth case, with the latter showing a 50% increase before 2020. The United States Department of Energy, in its recently released International Energy Outlook 1997, projects a 54% increase in global energy demand as early as 2015, half of this being due to rising demand in the newly emerging Asian economies, including China and India.

Globally, fossil fuels provide 87% of commercial primary energy. Nuclear power and hydroelectric each contribute 6%. The non-hydroelectric renewables, solar, wind, geothermal and biomass, constitute less than 1% of the energy supply. One third of commercial primary energy is consumed in electricity generation [2].

Although energy demand downturns do occur in specific countries and regions and at times of economic recession, it is clear that the nuclear industry operates in what is expected to be a globally expanding energy market. Although electricity generation is expected to continue to be the main application, further potential lies in expansion of nuclear energy into the non-electric sector. Currently, about 0.5% of nuclear power generation is used for non-electric applications [1]. Various district heating, industrial process and desalination applications exist in a number of countries, including Canada, China, Kazakhstan, Japan, Slovakia and the Russian Federation. The IAEA provides assistance to Member States in non-electric areas, addressing for example the increasing problem of potable water shortages by reviewing technical and economic aspects of the use of nuclear power for seawater desalination.

Nuclear Power Reduces Greenhouse Gas Emissions

Currently, nuclear power avoids annually about 8% of global CO_2 emissions from energy production, or more than 600 million tonnes of carbon (or 2,300 million tonnes of CO2) [5]. As more and more people become convinced of the potential consequences of global warming, and realise that the solutions are not going to be easy, the potential for nuclear power to play an important role in the future energy mix in various regions must inevitably become more widely recognised.

The five years since the Rio conference have solidified the international consensus that increasing greenhouse gas emissions will have serious global consequences. At the December 1997 Conference of the Parties to the United Nations Framework Convention on Climate Change in Kyoto, Japan, the world's nations gave formal approval to an agreement that would reduce greenhouse gas emissions by industrial countries. The European Union agreed to reduce its greenhouse gas emissions by 8% below 1990 levels, the United States by 7%, and Japan by 6%. Twenty-one other industrialized countries accepted similar binding targets, and the reductions are to be achieved between 2008 and 2012. All are committed to further cuts after that. The historic agreement is the first to require mandatory emissions limits of industrialized nations. The agreement has some major hurdles to pass before ratification, and developing countries have not committed to reductions.

To facilitate energy policy decision-making by Member States, the IAEA's comparative assessment programme is aimed at defining optimal strategies for the development of the energy sector, consistent with the aims of sustainable development. This programme focuses on developing and disseminating databases and methodologies for comparative assessment of nuclear power and other energy sources in terms of their economic, health and environment impacts; ensuring that the results of IAEA-supported assessments are made available to relevant national and international forums (such as the Intergovernmental Panel on Climate Change and the United Nations Framework Convention on Climate Change); and on enhancing the capability of Member States to incorporate health and environmental considerations in the decision making process for the energy sector.

Uranium-based Fuel Resources are Adequate for the Foreseeable Future

Once-through fuel cycles can be supplemented by increasing use of uranium and plutonium recycle and by future use of thorium. Additional large quantities of plutonium are available from dismantled warheads. Fast breeder reactors can extract up to sixty times as much energy from uranium as can thermal reactors. The increasing interest in additional international measures related to the production, transport, storage and disposition of separated plutonium prompted the IAEA to establish in 1998 an International Working Group on nuclear fuel cycle options as a mechanism for dialogue among Member States on plutonium and related fuel cycle issues.

Nuclear Power Can Compete with Other Energy Sources

Despite the prevailing low fossil-fuel prices, the generating cost of nuclear electricity continues to be competitive with fossil fuel for base-load electricity generation in many countries. Although the large capital investment required for nuclear power plants is a disadvantage, especially in developing countries, the nuclear fuel cycle cost is relatively low. Moreover, the prices of fossil fuels are likely to increase over the long term because the resource is limited and also if pressures are applied - policy or financial instruments, to discourage use; and there is still scope in the nuclear industry for rationalization, standardization, modular construction, shorter construction periods, higher burnup and simplification, resulting in better performance and lower generation cost. Nuclear generation can thus be expected to be more competitive with fossil fired plants in many areas of the world in the long run.

In the early years of the next century, however, nuclear utilities will experience an operating environment in which nuclear power plants will face increased competition, in an open energy market, with other suppliers of electricity. Data on operating costs will be analysed to determine whether the continued operation of nuclear power plants provides power to consumers at the least cost. This competitive environment has significant implications for plant operations, including efficient use of all resources; more effective management of plant activities, such as outages and maintenance; greater use of analytical tools to balance costs and related benefits of proposed activities; and sharing of resources, facilities and services among utilities.

In the face of this competitive pressure, nuclear power plants world-wide are showing a steady increase in the energy availability factor (defined as the ratio of the actual net energy generated in a given period expressed as a percentage of the maximum energy that could have been produced during that period by continuous operation at the reference capacity). An analysis of the data available in the IAEA Power Reactor Information System (PRIS) indicates that the world energy availability factor for nuclear power plants has increased from 70.1 percent in 1989 to 77.4 percent in 1996 [6]. Nuclear plant operators are achieving high availabilities through integrated programmes including personnel training, quality assurance, improved maintenance planning, as well as through technological advances in plant components and systems, and in inspection and maintenance techniques [7]. The IAEA emphasises improving the performance and reliability of nuclear power plants through the sharing of information and experience world-wide [6] , provides the PRIS database, which is available through the Internet, as an authoritative source of information for statistical analysis of nuclear power plant performance indicators, and conducts projects in nuclear power plant performance assessment.

ADVANCED REACTOR DESIGNS FOR THE NEXT CENTURY

Nuclear power programmes in Member States are making significant investments in technology and designs for the next century, focussing on substantial evolutionary improvements of reactor systems to further enhance their economics, reliability and safety. To support these programmes, the IAEA promotes technical information exchange and co-operation between Member States, provides a source of balanced, objective information on developments in advanced reactor technology, and publishes reports available to all Member States interested in the current status of reactor development [8,9,10,11,12]. These activities are conducted within the frames of International Working Groups for the major reactor lines: light water reactors; heavy water reactors, fast reactors and gas cooled reactors.

Advanced water-cooled nuclear power plants are being developed, that will improve economics, reliability, and further enhance safety to make the potential for significant harm to the public even more remote [13,14].

Four advanced reactor designs developed in the United States have been submitted to the U.S. NRC for certification. Two large evolutionary plants, the System 80+ of ABB Combustion Engineering and the ABWR of General Electric, received Final Design Approval in 1994 and received Design Certification in May 1997. The Westinghouse 600 MWe AP-600 is under review by the NRC, and a Final Design Approval is expected in 1998. The first-of-a-kind-engineering programme was completed for the ABWR in September 1996, and similar work on the AP-600 is underway with completion scheduled in 1998.

In Europe, Framatome and Siemens with their joint company, Nuclear Power International, together with Electricité de France and the group of “nuclear” German utilities are developing a new advanced PWR, the European pressurized water reactor (EPR), at 1500 MWe with enhanced safety features. The basic design of the EPR was completed in mid-1997, and the design is being reviewed jointly by the French and German safety authorities. Siemens is also, together with German utilities, engaged in the development of an advanced BWR design, the SWR-1000, which will incorporate a number of passive safety features. In Sweden, ABB Atom and Teollisuuden Voima Oy (TVO) of Finland, are developing the BWR 90 as an upgraded version of the BWRs operating in both countries. An adaptation of the Westinghouse AP-600 design to meet the requirements of the European utilities and the need for plants with higher power outputs (1000MWe), is underway in Europe.

In the Russian Federation, design work is underway on the evolutionary V-392, an upgraded version of the WWER-1000, on a mid-size plant, the WWER-640 (V-407) which incorporates passive safety systems, and on a more innovative, integral design, the VPBER-600.

In Japan, two ABWRs, the Kashiwazaki Kariwa units 6 and 7 have already been taken successfully into commercial operation. A 1400 MWe advanced pressurized water reactor (APWR) is being developed by Japanese utilities together with nuclear vendors, with construction of a twin unit being planned at the Tsuruga site. Development programmes for a Japanese simplified BWR (JSBWR) and PWR (JSPWR) are in progress jointly involving vendors and utilities. The Japan Atomic Energy Research Institute (JAERI) has been investigating conceptual designs of advanced water-cooled reactors with emphasis on passive safety systems. These are the JAERI Passive Safety Reactor (JPSR) and the System-Integrated PWR (SPWR).

In China, the AC-600 advanced PWR which incorporates passive safety systems for heat removal, is under development by the Nuclear Power Institute of China (Chengdu).

The Republic of Korea is developing the Korean Next Generation Reactor (KNGR), an evolutionary 4000 MWth PWR design. The basic design is currently being developed by Korea Electric Power Corporation (KEPCO) with the support of Korean nuclear industry. The goal is to complete a detailed standard design by the year 2000.

The continuing design and development programmes for HWRs in Canada are primarily aimed at reduction of plant costs and at an evolutionary enhancement of plant performance and safety. Two advanced versions; the 670 MWe CANDU-6 and the 900-1300 MWe CANDU-9, are under development within the evolutionary programme. Highly reliable and redundant measures and features to prevent and mitigate severe accidents are incorporated into the design of CANDU 9.

India is performing a design study of an advanced 220 MWe HWR which utilizes thorium fuel and boiling, light water coolant, and is developing a 500 MWe version of its standard HWRs.

PIUS is being developed by ABB Atom in Sweden with a nominal power output of 600 MWe. It is basically a pressurized water reactor (PWR) in which the primary system has been rearranged to accomplish an efficient protection of the reactor core by thermal-hydraulic characteristics, in combination with inherent and passive features, without reliance on operator intervention or proper functioning of any mechanical or electrical equipment.

Liquid metal cooled fast reactors (LMFRs) have been under development for more than 45 years. Five prototype and near-commercial scale LMFRs (BN350/Kazakstan, Phenix and SuperPhenix/France, PFR/UK, BN600/Russian Federation), with an output of between 250 and 1200 MWe, have accumulated more than 85 reactor-years of operating experience. Significant technology development programmes for LMFRs are underway in several countries, notably France, Japan and the Russian Federation. Introduction of additional fast breeder reactors in France has been postponed.

The prototype 280 MWe fast reactor Monju in Japan delivered electricity for the first time in August 1995 and was stopped temporarily after a sodium leak in December 1995. Design of a 660 MWe demonstration fast breeder reactor is in progress. Experience in the Russian Federation in the operation of the experimental and prototype fast reactors BR-10, BOR-60, BN-350 and BN-600 has been very good. Current efforts are directed towards improving safety, reliability and economics.

Elsewhere, work continues on the design of the 500MWe prototype LMFR at the Indira Gandi Center for atomic research in India. The Republic of Korea's LMFR programme anticipates a prototype by 2011. The Chinese Experimental Fast Reactor, CEFR-25, is planned for criticality in the year 2000.

Gas cooled reactors are of increasing interest for achieving high efficiency in the generation of electricity and in process heat applications. The primary focus is on the generation of electricity via the direct coupling of a gas turbine which can result in a net plant efficiency approaching 47%, and to evaluate the application of high reactor outlet gas temperature for industrial uses such as steam and carbon dioxide reforming of methane for the production of hydrogen and subsequent synthesis to other fuels such as methanol.

Two gas cooled test reactors, the high temperature engineering test reactor (HTTR) in Japan and the HTR-10 in China, are scheduled to commence operation in 1998 and 1999, respectively. These reactors will be able to produce core outlet temperatures approaching 950°C and will be utilized to verify basic technologies for advanced high temperature gas-cooled reactors (HTGRs) and to demonstrate nuclear process heat applications. Information from the operation of these reactors will be made available in support of a new IAEA co-ordinated research programme to evaluate HTGR performance.

Modular HTGRs coupled to gas turbine power conversion systems are currently under evaluation as high efficiency energy sources for the generation of electricity. A consortium consisting of General Atomics (United States), MINATOM (Russian Federation), Framatome (France) and Fuji Electric (Japan) are developing the Gas Turbine-Modular Helium Reactor which features an HTGR with prismatic fuel elements as the energy source. Conceptual design of this plant is now complete for initial deployment in the disposition of weapons plutonium. The state electric utility of South Africa, Eskom, is finalizing a technical and economic evaluation of a helium cooled pebble bed reactor of German design with a power output of ~228 MWth.

PREREQUISITES FOR ACCEPTANCE OF NUCLEAR POWER

The nuclear industry has been on probation since the Chernobyl accident in 1986. Keys to the acceptance of nuclear power are: prolonged operation without any serious accidents or releases of radioactivity into the environment, which requires vigorous and persistent maintenance of a global safety culture; proper implementation of nuclear waste disposal; and a safeguards system that is clearly seen to prevent diversion of nuclear material.

The global nuclear safety culture is extensively addressed by regulators in the Member States, and by operators who have the prime responsibility for nuclear safety, collaborating within the World Association of Nuclear Operators (WANO). The IAEA contributes to the global nuclear safety culture through the introduction of binding conventions and recommended standards, the provision of advisory services and the exchange of experience and information.

Legally binding conventions concluded under IAEA auspices include the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, which were drawn up in record time in 1986, following the Chernobyl accident. In 1996 the Convention on the Safety of Nuclear Installations entered into force and over 40 Member States are now party to it. A central provision calls for peer review, at meetings held at least every three years, of national reports demonstrating fulfillment of the various obligations under this Convention. In September 1997 a Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management was adopted. It has now been signed by over twenty Member States.

Safety standards, recommendatory in nature, form an important second component of the global nuclear safety culture. At the end of 1994 the new International Basic Safety Standards (BSS) for Protection Against Ionising Radiation and for the Safety of Radiation Sources were adopted. The IAEA's Nuclear Safety Standards (NUSS) programme has resulted in some 60 non-binding standards and supporting guides dealing with the principal aspects of nuclear power safety - from the siting to the operation of plants. The NUSS documents are the basis for a number of national laws and regulations. The first document in a comprehensive series of Radioactive Waste Safety Standards (RADWASS) was issued late in 1995. Regulatory authorities in Member States have been developing increasingly stringent national safety standards and are increasingly diligent in their application. The IAEA will continue to support Member States through information exchange on technical issues and will promote the adoption by Member States of complete sets of laws and regulations and the development of rigorous licensing procedures.

The provision of peer review and advisory services by international experts - the third component of the international nuclear safety culture - has enabled national operators and regulators to draw on the nuclear safety experience available world-wide. Among the services of the IAEA are missions by Operational Safety Review Teams (OSART), providing plant operators with recommendations and suggestions for strengthening safety performance. Teams for the Assessment of Safety Significant Events (ASSET) provide comprehensive investigations of incidents in the operation of nuclear power plants. Assessment of Safety Culture by Organizations Team (ASCOT) seminars give support targeted directly at safety culture by increasing the understanding of the concept of safety culture, it's development and how it can be assessed, so that plants can perform self-assessments.

The sharing of safety relevant information is the fourth component of a global nuclear safety culture. The correct understanding and assessment of nuclear accidents and incidents is an important part of experience sharing and learning from each other. The IAEA facilitates international meetings which allow such exchanges.

Nuclear waste disposal is often seen as the Achilles heel of the nuclear industry. Extensive research and development in many countries have led to the general conclusion that final disposal is technically feasible, but it still needs to be demonstrated convincingly to the public. That this has not been done is largely attributable to public scepticism or opposition and lack of the necessary political support.

Presently, high level wastes are being stored above or below ground, awaiting policy decisions on their long-term disposal.

Once nuclear wastes are placed in a repository, nuclear power plants will offer benefits from the relatively small volumes of such wastes compared to those of coal fired power plants which are dispersed in the atmosphere or on the earth's surface. These benefits can be appreciated by considering that a 1000 MW(e) coal plant, even with optimal pollution abatement equipment, will emit into the atmosphere 900 tonnes of SO_2 per year; 4500 tonnes of NO_x; 1300 tonnes of particulates; and 6.5 million tonnes of CO_2. Depending on the quality of the coal, up to 1000 000 tonnes of ashes containing several hundreds of tonnes of toxic heavy metals (arsenic, cadmium, lead, mercury) will have to be disposed of. By contrast, a nuclear plant of 1000 MW(e) capacity discharges annually some 35 tonnes of highly radioactive spent fuel, essentially all of it safely contained, together with 800 tonnes of low and intermediate level radioactive waste. Although the amount of radioactive waste is small, future nuclear power designs and fuel cycles can be modified to even further decrease the quantities generated. Innovative actinide burning reactors might also in the future transmute long lived radioactive elements into short lived—elements.

The IAEA plays a major role in facilitating safe management of radioactive wastes. Support is given to the collection, assessment and exchange of information on waste management strategies and technologies for nuclear power plants, fuel cycle facilities, radioisotope applications, research activities and waste site restoration. The IAEA provides general technical guidance, assistance in technology transfer and promotes international collaboration in optimising the development and establishment of technical waste management infrastructures and programmes in Member States. Long term prospects of regional fuel cycle facilities will be examined to provide new opportunities for developing countries with limited national resources to resolve their waste management problems in a cost-effective manner. Scientific and technical information are exchanged through the International Radioactive Waste Technology Advisory Committee.

The IAEA plays a vital role in operating the **international safeguards system** that serves the overall objective of non-proliferation of nuclear weapons. It also provides services designed to strengthen the physical protection of nuclear materials and to combat the threat of illicit trafficking in such materials. The safeguards system of the IAEA has been strengthened, via the so-called 93+2 programme, with requirements for more information and for allowing safeguards inspectors greater access to installations, even to undeclared nuclear facilities. Through a co-operative activity between the IAEA Departments of Nuclear Energy and of Safeguards, guidelines for design measures to facilitate the implementation of safeguards for future water cooled nuclear power plants have been prepared [15].

CONCLUSION

Expansion of nuclear energy has been dampened in the past decade by a number of factors. However, the prospects for the long term are positive. The global energy market is expanding and nuclear energy has the potential to increase market share by diversification into non-electric use of energy. Nuclear energy has two fundamental competitive advantages: long-term security of supply and the potential for reduction of the emission of greenhouse gases. Significant investments are being made in advanced nuclear reactor designs and technologies, ready for the next century. Continued safe operation of current reactors, implementation of nuclear waste disposal technology, and an improved safeguards regime should reduce concerns about nuclear power. Nuclear power can be expected to make an important contribution to global energy needs and to the abatement of greenhouse gases in the next century and beyond.

For four decades of the current century, the IAEA has fulfilled the objective expressed in Article II of the IAEA's Statute: " The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, insofar as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose". The IAEA will continue to play a major role as the nuclear industry faces the challenges and opportunities of the 21st century.

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