Nuclear power development: Global challenges and strategies

Today's global pattern of energy supply is not sustainable, and the future must see a mix of fuels for environmental and other reasons

by Victor M. Mourogov

Five years after the Earth Summit in Rio de Janeiro, a Special Session of the United Nations General Assembly in June 1997 examined progress toward the goals of sustainable development. Sustainable development is linked to protecting the environment and thus unquestionably to the supply and use of energy.

With a combination of industrialization, economic development, and a projected doubling of the world's population in the 21st century, global energy consumption will surely continue to increase. Growth will be driven principally by the demand in developing countries. They now have 75% of the world's inhabitants but consume only 31% of all energy produced worldwide. Conservation and improved efficiency in energy use will restrain but not stop demand. The World Energy Council (WEC) projects growth in energy demand of anywhere between 50% and 300% over the next five decades, depending on environmental and economic factors.

The global energy issue

In view of projected energy demands, today's global pattern of energy supply is not sustainable. There is a solid international consensus that heavy dependence on fossil fuels — which today account for almost 90% of the total energy supply — must be controlled. Their use adversely affects the atmosphere through emissions of greenhouse gases along with other noxious gases and toxic pollutants.

Though it is not problem free, nuclear power is recognized as having a clear advantage in contributing to the goals of sustainable development. For its entire energy chain from fuel production to waste disposal, it has limited emissions of greenhouse gases and other pollutants. Nuclear power currently provides about 6% of global energy and 17% of global electricity supply. Nearly 480 nuclear plants are operating or being built in 32 countries.

Despite the record, there is no international consensus concerning nuclear's future role. The policies of a few countries are absolutely opposed to nuclear power. While some countries are decidedly positive, the majority are passive at best. While nuclear power stagnates in Europe and North America, it continues to expand in Asia. Countries in Eastern Europe and the former Soviet Union, heavily dependent on nuclear power, are experiencing serious difficulties due to a breakdown in the infrastructure necessary to keep the nuclear power plants operational.

The future will see a mix of energy sources. The makeup of this mix cannot be precisely defined — it will depend not only on environmental considerations, but also on technological, policy, and market factors. For many years, fossil fuels are expected to continue to play a major role in energy production. With adequate support the share of new renewable energy supplies should increase. The WEC expects renewables to reach a global energy share of between 5% and 8% in the next 25 years. Hydroelectric's share will likely remain around the current 6%.

The potential of nuclear power

The challenge for the nuclear community is to assure that nuclear power remains a viable option in meeting the energy requirements of

Mr. Mourogov is the IAEA Deputy Director General heading the Department of Nuclear Energy.

the next century. It could be a major provider of electricity for baseload as well as for urban transport in megacities. It can play a role in non-electric applications in district heating, process industries, maritime transport, water desalination, hydrogen production, and for applications in remote areas. It can contribute substantially to the security of energy supply and it has the potential to be an almost inexhaustible long-term energy resource through the use of breeder reactors.

However, the current lack of public support could unquestionably constrain the introduction of new plants. It will be necessary to openly discuss the concerns that have limited nuclear power's acceptance. But discussions of health and environmental impacts along with severe accidents and waste disposal must not be done in isolation as is too frequently the case. As no energy source is risk free, comparative impacts of the various energy systems must be extensively reviewed. Studies of nuclear, fossil, and renewable energy chains show that there are significant issues and impacts inherent in all options.

Authoritative comparative assessments illustrate the potential of nuclear power to mitigate energy-related health and environmental damage — it can be shown to be one of the most environmentally acceptable means of generating electricity. If external factors, such as the societal costs of climate change, environmental damage, and health effects were included in all analyses, a clear nuclear advantage would arise over fossil fuels — and the economic competitiveness of nuclear power in a radically changing financial environment would escalate.

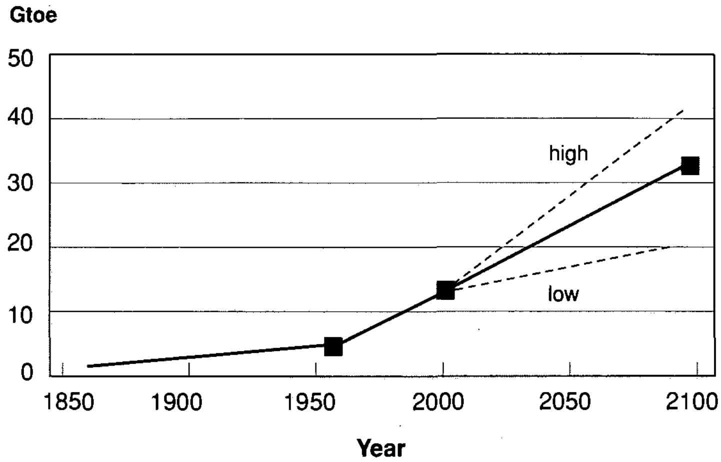
This article highlights key factors that will determine today and tomorrow's optimal energy strategies. It addresses methods to utilize the high potential energy content of uranium. Plutonium use as fuel in nuclear reactors is discussed as is the future potential of a thorium fuel cycle. Various strategies to increase the economic viability of nuclear power are brought out. Technological means to further minimize environmental impacts and to enhance safety are covered as they are a major factor in public acceptance. Also covered are advances anticipated by mid-century in nuclear reactor and fuel cycle technologies.

Fuel cycle and reactor strategies: A look at the key factors

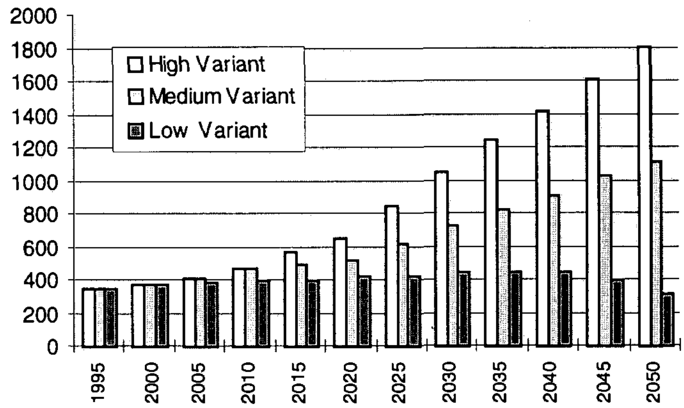
If a significant contribution from nuclear power is to take place by the middle of the next century, a large amount of new generating capacity would be required, averaging as high as 20 new units annually. There are a number of issues relevant to the fuel cycle and the type of reactor desired that must be dealt with now in order to provide the best conditions for an increased nuclear role.

The IAEA's recent Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities (held in Vienna, Austria, 2-6 June 1997) addressed a broad range of topics. They included those brought about by the slowdown in nuclear power growth and the large amounts of plutonium expected to be recovered from dismantled nuclear warheads. One Key Issue Paper

Global Energy Use
Gigatonne oil equivalent (Gtoe)



World Nuclear Capacity
Gigawatts-electric



specifically focused on future fuel cycle and reactor strategies.

In an increasingly competitive and international global energy market, a number of key factors will affect not only the energy choice, but also the extent and manner in which different energy sources are used. These include:

- optimal use of available resources;
- reduction of overall costs;
- minimizing environmental impacts;
- convincing demonstration of safety; and
- meeting national and global policy needs.

For nuclear energy, these five factors will determine the future fuel cycle and reactor strategies. As the objective is to optimize these factors, they will be discussed sequentially under corresponding headings; maximizing resource utilization, maximizing economic benefits, maximizing environmental benefits, maximizing reactor safety, and satisfying key policy needs.

Although obtaining public acceptance has not been included as a key factor, it is in reality a vital one for nuclear energy. It will be necessary to communicate the real benefits of nuclear power to the public and policy makers in an open and credible manner. The growing public reluctance, particularly in developed countries, to accept new large industrial facilities impacts policies in the entire energy sector and affects the implementation of all power plant projects.

Maximizing resource utilization. Known and likely resources of uranium should assure a sufficient nuclear fuel supply in the short and medium term even with reactors operating primarily on once-through cycles with disposal of spent fuel. However, as uranium demand increases and reserves are decreased to meet the requirements of increased nuclear capacity, there will be economic pressure for the optimal use of uranium in a manner that utilizes its total potential energy content per unit quantity of ore. A variety of means are available to accomplish this during the enrichment process and at the operational stage. Over the longer term, recycling of generated fissionable material in thermal reactors and introduction of fast breeder reactors will be necessary. Thorium could also be a valuable energy resource in the longer term.

Uranium fuel cycle. Isotopic separation technology enables lowering the uranium-235 content in the enrichment process waste tailings. This results in extraction of more of the original 0.7% fraction of this fissionable isotope existing in the natural uranium ore that consists primarily of non-fissionable uranium-238. At the operational stage, higher fuel burn-up cycles will utilize more of the uranium-235 contained in the enriched uranium fuel elements — concurrently reducing the amount of spent fuel relative to the energy produced.

However, reprocessing of spent fuel instead of disposal would allow the recycling of generated plutonium through mixed oxide fuel in thermal reactors as well as in fast breeder reactors and also make available uranium with its fissionable isotopes that are contained in spent fuel. Reprocessing would significantly increase the energy potential of today's uranium resources — theoretically by a factor of around 70 — and also substantially reduce the quantity of troublesome long-lived radioactive elements in the remaining waste. By far, recycling provides the best use of available uranium resources. The current policy of interim spent fuel storage before ultimate disposal preserves the potential for future reprocessing to extract fissionable material, particularly plutonium.

Thorium fuel cycle. Although uranium is likely to remain the main natural resource for nuclear power systems, in the longer term the use of fertile thorium as a feed material is possible. While uranium contains a fissionable isotope, thorium does not. It must be enriched with either fissionable uranium-235 or plutonium to start the fuel cycle. The uranium-233 that is subsequently generated in the reactor from thorium conversion is fissionable. The thorium fuel cycle, with its lower operating fuel temperatures, has advantages in the physical performance of fuel elements and also with respect to the characteristics of the core physics.

The existence of indigenous thorium in a number of countries that have limited uranium deposits would make this an attractive option. Thorium-based fuel cycles have been developed in a number of countries. Among these are the United States, Germany, India, the United Kingdom, Japan, and Canada, with the first three having successfully demonstrated their use in power reactors. The thorium fuel cycle can be used in all types of current systems — light and heavy water as well as high temperature gas and fast reactors — without requiring significant changes in the reactor design or safety concepts.

However, present knowledge of the extent of thorium resources in the world is poor even though extensive deposits with high grade ore have been found. Extraction of thorium from ores is a somewhat difficult process, and its economics are not established. There are also difficulties of separation of the produced uranium-233 from the spent fuel. But the remaining waste is significantly easier to deal with than the waste from the current uranium-based fuel cycle without reprocessing.

Maximizing economic benefits. As fuel costs are relatively low, reduction of overall costs by decreasing development, siting, construction, operation, and initial financing expenses is essential to the overall economic viability of nuclear energy. Removing the uncertainties and variability in licensing requirements, particularly before commissioning, would allow for more predictable investment and financial strategies.

Development costs. The high costs associated with new design development will likely result in less expensive evolutionary improvement of today's reactor systems rather than the more expensive introduction of revolutionary new designs and technologies. Governmental development funding has substantially decreased over the years and as with all mature technologies, the source of funding will shift entirely to the private sector.

Capital costs. The need to reduce high initial capital costs will encourage economies in siting and construction. It will lead to multi-unit sites at existing locations that will also maximize infrastructure investments. There will be more emphasis on plants with standardized systems and components as successfully employed in France. Plant size and unit power levels will be matched to regional needs and the choice of suppliers will be based on long-term economics rather than on short-term advantages.

Operations. In the operational area, reduction in costs will require high availability and load factors brought about by high quality systems, long core fuel cycle periods, short shutdown times and the ability to rapidly return to power. There will be a continued evolution of separate organizations providing various plant and fuel cycle services, particularly on a regional basis.

Licensing. Some of the high capital costs of new facilities and extended construction periods are related to the uncertainties and demands in licensing requirements. Uncertain waste management and decommissioning requirements and costs deter investments. These factors may lead to a rationalization of the licensing process leading to more certainty in regulation and a concurrent decrease in the time from site selection to operation. Waste and decommissioning requirements based on comparative assessments of other industrial practices may lead to a more practical approach to radioactive material without compromising safety.

Financing. Innovative and novel investment strategies will be needed to meet evolving and changing investment goals. The large initial capital investments required for nuclear power projects could be easier to raise in the framework of multinational funding arrangements. Build, operate and transfer arrangements may be used in developing countries that allow for adequate returns on non-domestic investments before shifting ownership. Incremental investment strategies through modular energy systems would also decrease initial financing needs.

Maximizing environmental benefits. Although nuclear energy has distinct advantages over today's fossil burning systems — in terms of fuel consumed, pollutants emitted and waste produced — further reducing environmental concerns can have a major influence on public attitudes.

As the overall health and environmental impact of the nuclear fuel cycle is small, attention will be directed at improved techniques to deal with radioactive waste. This would support global sustainable development goals and at the same time increase competitiveness with other energy sources that will be required to adequately deal with their waste. Reactor systems and fuel cycles can be adjusted to minimize waste production. Design requirements to decrease waste quantities and volume reduction techniques such as ultra-compaction will be employed.

Advanced technologies to contain and immobilize high-level waste are under development. But, of most significance, programmes are currently in place to demonstrate the adequacy of deep underground disposal of high-level waste. The construction and operation of a geologic repository in the next decade could allay public concerns over the safety as well as cost of disposal. If deemed necessary, the long-lived isotopes (actinides) that are radioactive for many thousands of years can be transmuted in actinide burning reactors. The necessary technology exists for these reactors and their associated chemical separation plants. As already noted, the thorium fuel cycle results in less long-lived isotopes and lower disposal requirements.

Maximizing reactor safety. With more than 430 reactors operating for more than 20 years on average, nuclear power generally has an excellent safety record. But the Chernobyl accident in 1986 demonstrated that a very severe nuclear accident has a potential to cause national and

Fuel and Waste Comparisons

1000-MWe electricity plant in tonnes/year

Nuclear

Fuel: 27t (160t Natural uranium/year)

Wastes: 35t (high level)
310t (intermediate)
460t (low level)

Coal*

Fuel: 2.6 million t
(5 trains of 1400t/day)

Wastes: 6.5 million t CO_2
900 t SO_2
4500 t NO_x
320,000 t Ash (with 400t toxic heavy metals)

*Equipped with latest pollution abatement technology.

regional radioactive contamination. Although safety and environmental impacts are becoming a key issue for all energy sources, many in the general public perceive nuclear power as particularly and intrinsically unsafe. The safety concerns coupled with the associated regulatory requirements will, in the near term, continue to exert a strong influence on nuclear power development. In order to reduce the magnitude of real and perceived accidents, a number of approaches will be used in new facilities.

Extraordinarily effective barriers (such as double containments) will reduce the likelihood of significant off-site radiological accident consequences to an extremely low level to eliminate the need for emergency action plans. Enhancing the integrity of the reactor vessel and reactor systems will also decrease the likelihood of on-site consequences.

International collaboration will provide reactor and system designs that incorporate globally accepted safety and engineering standards. It will contribute to assuring safety worldwide and encourage country-of-origin licensing as an acceptable basis for national licensing of imported reactors. Plant designs and processes are more intrinsically safe by incorporating passive safety features rather than active protection systems. High temperature gas-cooled reactors that employ ceramic graphite fuel can limit the potential for the release of radioactive material and may emerge as a viable option.

Continued development of a strong global nuclear safety culture brought about by international collaborative efforts aimed at strengthening safety worldwide would contribute to public awareness of the strong international commitment to assuring safety. A wide range of international agreements, non-binding safety standards and international review and advisory services already exists in what is now distinctly seen as an international nuclear safety regime. Highly visible components are the Convention on Nuclear Safety, which entered into force in October 1996, and whose Contracting Parties recently agreed on the review process for the Convention's implementation; and the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, whose adoption is expected at a Diplomatic Conference this year.

Unquestionably, the most convincing demonstration of safety will be through the safe performance of existing plants and the avoidance of any major incident in the future.

Satisfying key policy needs. Energy independence along with non-proliferation concerns and excess military plutonium are high on the list of policy factors at the national and international level that strongly influence the nuclear option.

In a political world, energy independence through security of energy supply and a balanced mix of energy sources are paramount national interests. With nuclear power, security of supply concerns are lessened as adequate strategic inventories can be relatively easily established with low financial costs. Today's global energy mix has an almost 90% fossil component. Clearly, where indigenous fossil fuel resources are lacking, nuclear energy can contribute substantially to the energy mix as it does in France, the Republic of Korea, and Japan.

The potential for nuclear materials and technologies to be diverted to nuclear weapons production is a valid concern. The international community has recognized the proliferation risks and measures exist to prevent diversion of fissile materials. These include the Treaty on the Non-Proliferation of Nuclear Weapons and associated safeguards agreements with the IAEA, as well as a number of other multilateral agreements. To further reduce the risks of proliferation, design efforts are under way for diversion resistant reactors and fuel cycles that generate fissile material unsuitable for weapons use.

To deal with present stockpiles of military plutonium, proposals exist for their use in mixed oxide fuels in the current generation of water reactors. Employment of a fast breeder reactor strategy would reduce the plutonium stockpile that now exists in spent fuel and over the long term could eventually eliminate its accumulation.

Direction of IAEA programmes related to nuclear power development

Taking into account the current situation of nuclear energy in the world, a stronger initiative on an international level is required to realize the technology's potential benefits. The Agency continues to play a catalytic role in co-ordinating actions, covering the whole range of energy issues, undertaken by Member States and different international or specialized organizations. The IAEA's programmes and activities will be described under the following headings: nuclear power, nuclear fuel cycle, waste management technology and comparative assessment of energy sources.

Underlining the work ahead is a reinforced global commitment to safe nuclear operations through legal agreements, safety standards, and associated expert services. *(See box.)* The declaration of the April 1996 Moscow Summit reiterated that safety is the first priority in nuclear activities. Furthermore, it is to be expected that safety targets will continue to rise and this will require continuous effort and vigilance by the IAEA and its Member States to ensure that adequate levels are maintained.

Nuclear power. The IAEA's efforts in nuclear power will focus on the contribution of nuclear energy to sustainable development, with emphasis on:

- promoting design and operation measures necessary to achieve safe development of nuclear power;
- assisting developing Member States in planning and implementing nuclear power programmes and in improving the management of nuclear power projects and operating plants;
- improving operating performance and reliability of nuclear power plants through sharing of operating experience and information worldwide in all areas, including training and qualification of personnel.

One mechanism used by the IAEA to keep abreast of the technological developments in a given area is the constitution of an international working group (IWG) for that area. *(See box.)* It consists of top experts from different Member States. The IWG meets periodically to review the current status and future directions of activities in the area concerned and advises the Agency on the programme of activities necessary to meet the needs of Member States.

Through the IWGs on advanced reactor technologies, the Agency will encourage an international exchange of information on non-commercial technology and co-operative research. Another important function will be to assist countries in the preservation of key technological data on advanced nuclear power systems. The Agency will also continue to provide a forum for the review of information on the development of innovative nuclear energy systems such as:

- advanced nuclear reactors with passive safety features;
- thorium fueled reactors;
- fast reactors cooled by lead or lead/bismuth;
- accelerator driven and hybrid fusion/fission concepts.

A new area of activities relates to the current need to examine the possibility of civilian use of

Global Framework of Nuclear Safety

Legally binding international agreements and conventions have been adopted and cover a range of subjects. The subjects include:

- ***Civil Liability for Nuclear Damage***
- ***Physical Protection of Nuclear Material***
- ***Early Notification of a Nuclear Accident***
- ***Assistance in the Case of a Nuclear Accident or Radiological Emergency***
- ***Nuclear Safety***
- ***Safety of Spent Fuel Management and Safety of Radioactive Waste Management***

Non-binding common nuclear and radiation safety standards include:

- ***Basic Safety Standards for Radiation Protection***
- ***Safety Fundamentals***
- ***Nuclear Safety Standards Programme***
- ***Regulations for the Safe Transport of Radioactive Materials***
- ***Radioactive Waste Safety Standards***
- ***Safety Guides and Practices***

International Working Groups in Areas of Nuclear Power

- ***Advanced Technologies for Light-Water Cooler Reactors***
- ***Advanced Technologies for Heavy-Water Cooled Reactor***
- ***Fast Reactors***
- ***High Temperature Gas-Cooled Reactors***
- ***Life Management of Nuclear Power Plants***
- ***Nuclear Power Plant Control and Instrumentation***
- ***Nuclear Power Plant Personnel Training and Qualification***
- ***Water Reactor Fuel Performance and Technology***

military nuclear technologies developed for naval and space applications. Another concerns desalination. An important event was the May 1997 International Symposium on Desalination of Seawater with Nuclear Energy in the Republic of Korea which reviewed experience. Results of this symposium will be utilized to define more precisely the IAEA's work in this area.

Nuclear fuel cycle. Among key topics addressed in the recent IAEA nuclear fuel cycle symposium were the comparative assessment of different options for development of the fuel cycle, management of spent fuel and plutonium, and disposal of radioactive waste. The volume of spent fuel in interim storage at both power and research reactors is growing and the long-term storage of spent fuel in ageing facilities will become an increasingly crucial issue regardless of the management option chosen. Identification and mitigation of environmental, health and safety vulnerabilities of ageing spent fuel will be emphasized and activities relating to exchange of information, experience and advice on technical solutions in this area will be expanded.

With regard to management of plutonium from spent fuel and dismantled warheads, there is an increasing interest in additional international measures to address issues related to its production, transport, storage, and disposal.

Waste management technology. The focus of activities relating to radioactive waste management will be on the following:

- collection, assessment and exchange of information on waste management strategies and technologies;
- provision of general technical guidance, assistance in technology transfer, and promotion of international collaboration;
- examination of the long-term prospects of regional waste management facilities to provide new opportunities to developing countries in resolving their waste management problems in a cost-effective manner.

Comparative assessment of different energy sources. The IAEA programme on comparative assessment of sources of energy will focus on:

- comparative assessment of economic, health, and environmental aspects of energy systems and introduction of the results into the process of energy policy formulation and electricity system expansion planning;
- enhancement of the capability of Member States to incorporate health and environmental considerations in the decision making process in the energy sector;
- provision of a basis to define optimal strategies for the development of the energy sector, consistent with the aims of sustainable development.

A key element is the development and dissemination of databases and methodologies for comparative assessment of energy sources in terms of their economic, health and environmental impacts. Consideration will also be given to dealing with energy demand and supply issues outside the electricity sector.

Attaining environmental goals

The world's record of energy use shows that continuing the current dependence on fossil fuels is not sustainable. Nuclear power can play a role in mitigating the detrimental environmental impacts of energy use. With an increased nuclear role, the dominant reactor types to mid-century will be the light- and heavy-water reactors with improved economics and safety systems. High temperature gas-cooled reactors may gain a role particularly for specialized applications. Thorium-fueled reactors would have a marginal role as it is unlikely that the supporting infrastructure for its use will be developed. Efforts will continue to preserve the potential of fast-breeder reactors and they could be introduced gradually by mid-century.

To make nuclear energy more economically competitive, novel financing methods will have to be developed. Moreover, measures to gain public acceptance will be necessary. The adequacy of waste management policies and the disposal of high-level waste will be demonstrated through selection and use of geologically acceptable depositories. To maintain and enhance nuclear power's safety and performance record, there will need to be continued vigilance to improve safety through design, and to implement an effective operational safety culture and international safety agreements.

The IAEA will have to play an increasingly important role in co-ordinating the efforts of Member States and other international organizations in order to realize the potential benefits of nuclear energy for the world's sustainable development. An important element of programmes will be improving regional and international co-operation and sharing of infrastructure facilities, developmental costs, and operational experience to sustain the development of nuclear technology in a safe, reliable, and economic manner. ❐