The Uranium Institute 25th Annual Symposium
30 August-1 September 2000: London

The Need for Innovative Nuclear Reactor and Fuel Cycle Systems

Victor Mourogov

Nuclear power today is at a turning point, with no consensus concerning its future role. The following facts support this statement:

- Nuclear energy has grown from a new scientific development to being a major part of the energy mix in several of the 32 countries now using nuclear power. Besides providing electricity it contributes to achieving a number of policy goals, including ensuring energy independence, helping to keep the air clean and reduce carbon emissions. In 1999 it supplied more than one-sixth of global electricity. The majority of currently operating nuclear power plants perform well.[1] Table 1 shows a regional breakdown of presently operating reactors.[2]
- Continuing growth in population and energy demand, particularly in developing countries, in combination with further experience with and understanding of the global climate change phenomenon, emphasise a global imperative for a rapid and extensive deployment of non-fossil-fired plants. Nuclear power is the only mature non-carbon electricity generation technology that can significantly contribute to the long-term global sustainable energy mix. The recent Intergovernmental Panel on Climate Change (IPCC) scenarios foresee a significant potential for nuclear energy growth — from the current 6% of primary energy to between 10% and 30% by 2100.[3] This would imply an increase in world nuclear power capacity from the present 349 GWe to 2000–5000 GWe by 2050.[4]

Against this background, one would expect to see a rising trend for nuclear power generation in the near and foreseeable future. Yet, that is not the case:

- There are no commitments in North America and Western Europe for construction of new nuclear power plants in the near future, and two countries have decided to phase out existing nuclear power plants (NPPs).
- Although many developing countries in different regions of the world have been considering the use of nuclear power for a long time, few of them have actually yet done so.
- Nuclear power capacity continues to grow at a modest level mainly in a limited number of countries in East Asia and Eastern Europe.
- Globally, the number of NPP construction starts peaked in the 1970s and connections to the grid in the 1980s, but current levels of both are far below the values achieved earlier. There is no indication that this global picture will change significantly in the coming decade.

The main issues hindering further global nuclear power growth are different for different regions. Nuclear power development faces serious challenges of an economic and political nature in the two regions with the maximum experience in nuclear power development: North America and Western Europe. In developing countries the main issues are lack of adequate infrastructure, particularly in the back-end of the fuel cycle, lack of expertise in nuclear technology and its safety culture, as well as financing issues.

Political concerns on nuclear waste, safety and non-proliferation are also hindering the development of nuclear power. If nuclear power is to contribute in significant ways to meeting future energy demands, these issues, real or perceived, must be addressed. This is a particular challenge for developing countries that need electricity to mitigate the burdens of poverty and meet basic human needs. More must be done to assist developing countries interested in pursuing the nuclear option for electricity generation.

Each issue can be addressed through efforts in three interrelated areas:
- technology,
- legal and institutional framework,
- oversight and control.

In each of these interrelated areas, various steps have been taken and are being pursued. Progress is being made. But we should admit that what has been done is not enough to secure the future of nuclear power. Additional efforts are needed in all of these areas. While admitting the importance of efforts in the areas of legal and institutional frameworks as well as in oversight and control, we should always keep in mind that most industrial development has resulted from technological breakthroughs.

The concerns noted above are best addressed first through technological advances, and then through legal commitments, and finally through administrative means, including regulatory or verification arrangements where appropriate. This paper reviews the major challenges to future nuclear power development and discusses the need for international cooperation in innovative R&D activities to ensure full participation of nuclear power in the world energy market.

Nuclear Power Challenges

Economic Competitiveness & Infrastructure Compatibility
The availability of cheap natural gas and technological advances in gas turbine and coal technologies have reduced the economic attractiveness of new NPPs in countries with easy access to natural gas or coal. High up-front capital costs, relatively long construction times and political uncertainty have often more than offset the nuclear fuel cost advantage. New reactor and fuel cycle designs are aiming to reverse this trend and to enhance nuclear power’s overall advantages in future generations of nuclear plants.

Evolutionary nuclear power designs explore avenues to lower costs and increase safety by using modern control technology, simplifying safety systems, making use of passive design features and capitalising on economies of scale. Several such advanced reactors are commercially available.

It is expected that in the coming decades orders for evolutionary-design advanced reactors will be mainly from Japan and some developing Asian countries, where much of the future increase in electricity demand is projected to take place against a backdrop of limited domestic energy resources and no easy access to natural gas. Russia is also planning to deploy new NPPs, taking advantage of its accumulated experience in domestic nuclear power development to free gas supplies for increased exports to Western Europe.

For Western Europe and North America, studies by the IAEA, the International Energy Agency (IEA) and the OECD Nuclear Energy Agency (NEA) have all shown that given present overcapacity and competitive pricing in electricity markets, it will be difficult for relatively high cost evolutionary-design new nuclear power plants to be competitive, especially in regions with easy access to relatively cheap natural gas. The possible introduction of carbon taxes at acceptable levels in the coming decades in these regions would probably not significantly change the relative competitiveness of nuclear power plants and gas fuelled plants.

There is an understanding that evolutionary-design advanced reactors are very important for the continuation of nuclear power development in the near future. Nevertheless they cannot be considered from an economic point of view as a basis for a large-scale deployment of nuclear power at a global level.

There is a need, in addition to evolutionary systems, to develop innovative designs with much shorter construction periods and with significantly lower specific capital costs.[5] These designs should be attractive to the deregulated markets in Western industrialised countries when the time comes to replace existing reactors. The new designs should also be attractive to developing countries with small electricity grids, or in regions without grid connections, or for non-electricity applications such as district heating and desalination. Whether it should be the same type of reactor and fuel cycle system for both industrialised and developing countries is a question to be answered.

Nuclear Safety

The International Nuclear Safety Advisory Group (INSAG) has suggested requiring that future nuclear plants be safer by a factor of 10 than the targets set for existing reactors (i.e. targets of 10^{-5}/year for core damage and 10^{-6}/year for large radioactive releases for future plants).[6]

It is stated in the INSAG-12 report that: “Another objective for these future plants is the practical elimination of accident sequences that could lead to a large early radioactive release, whereas severe accidents that could imply late containment failure would be considered in the design process with realistic assumptions and best estimate analysis so that their consequences would necessitate only protective measures limited in area and in time.”

Evolutionary designs explore avenues to increase safety which include using modern control technology, simplifying safety systems, making use of passive designs and extending the required response times for safety systems actuation and operator action. A primary goal could be a level of confidence in plant safety sufficient to eliminate the need for detailed evacuation plans, emergency equipment, and periodic emergency evacuation drills.

However, in spite of the evolutionary improvements in safety, support for nuclear power has not increased in Western Europe and North America. There are different explanations given for this, but one strong reason is that, given that there have been significant accomplishments in the area of safety, other issues (such as economics, spent fuel and nuclear waste management) have replaced improvement of existing safety features as the greatest challenge to the future development of nuclear power.

The situation is different in developing countries where most new reactors are expected to be built. These countries are more likely to profit from the enhanced and passive safety features of the new generation of reactors with a stronger focus on effective use of intrinsic characteristics, simplified plant design, easy construction, operation and maintenance.

Spent Fuel and Waste Management

Although the volumes of nuclear waste are small compared to those from other forms of electricity generation, spent fuel and radioactive wastes from nuclear power plants and spent fuel reprocessing — and ultimately from plant decommissioning — still need to be managed safely.

Spent fuel can be safely stored for long periods in water-filled pools or dry facilities, some of which have been in operation for 30 years. Shortage of capacity for spent fuel storage is today's eminent issue in several countries where long-term waste disposal policy remains unsettled. The scientific and technical communities generally agree that geologic disposal of spent fuel or high-level radioactive waste from reprocessing can be carried out safely in stable geologic formations. However, site selection is a major political issue in most countries developing such facilities and no such commercial facility has yet been authorised. For now most high-level waste from commercial nuclear power is either stored on-site or transported to interim storage sites.

The absence of demonstration of a permanent waste disposal facility has exacerbated political concerns, particularly in Western industrialised countries and countries with small territories. This has introduced uncertainties regarding future operation, political willingness and financial viability. Licensing and opening of disposal facilities in the countries currently engaged in studies of deep geological disposal would provide a convincing demonstration that it can be done**.**

Some in the nuclear community think that development of innovative concepts for nuclear fuel cycles aimed at reducing nuclear waste volume and toxicity, and enhancing safety and cost-effectiveness of the fuel cycle, might mitigate political concerns in this area.

Countries with small nuclear programmes (one or a few reactors), or having fragile economies, generally lack the resources to develop any type of back-end fuel cycle services, including geologic repositories. Here, institutional approaches are used, including agreements for return of spent fuels. New approaches should be analysed, such as development of multinational back-end fuel cycle centres. The IAEA is examining factors that would need to be addressed for this crucial issue.

Non-Proliferation

Adequate protective measures and a robust international framework are essential to prevent unauthorised possession of nuclear materials and other dangerous radioactive materials, and to prevent the wilful destruction of nuclear installations or the intentional dispersal of such materials in transit. Avoidance of any potential linkage between nuclear power and nuclear weapons is central to the international non-proliferation regime, and serves as the basis for IAEA safeguards.

In the aftermath of events in Iraq and the Democratic People's Republic of Korea, the international non-proliferation regime has been extended and strengthened. This includes increased willingness of states to refrain from assisting potential proliferators from acquiring key technologies and know-how, improved supplier controls on sensitive materials, facilities and equipment, and strengthened IAEA safeguards — especially in relation to their ability to detect undeclared enrichment and reprocessing operations.

A large worldwide increase in the number of NPPs and the consequent increase in the amount of spent fuel containing plutonium are concerns for IAEA safeguards, but even more so would be the spread of critical uranium enrichment and plutonium extraction technologies. The costs of inspections required to provide an adequate degree of assurance that all states continue to honour their non-proliferation undertakings vary widely, depending on the nature of the technology employed. If a light water reactor is the baseline, the inspection effort for an on-load power reactor is approximately five times greater; a uranium enrichment plant ten times greater; and a chemical reprocessing plant with traditional plutonium extraction technologies approaches 100 times greater.[5]

Innovations in reactor designs and fuel cycle arrangements are being pursued with the aim of allowing substantial expansion of nuclear power, including in developing countries, while minimising access to nuclear materials for use in weapons or other explosive devices, and to the technologies allowing their production.

Availability of Fissile Material

An assured, economically accessible and environmentally benign fuel supply should contribute to large-scale nuclear energy development. Naturally occurring uranium is a finite resource. Presently known uranium reserves are sufficient to fuel the world's existing reactors well through the first half of the twenty-first century. Thorium is another fuel candidate for nuclear power. Highly enriched uranium and plutonium from dismantled weapons programmes will also add to nuclear resources.

There will be no major problem in the case of a doubling or tripling of the world nuclear power capacity. Of course, as with any natural resource, higher demand would raise prices and stimulate exploration and expand the resource base.

But we should not forget that existing and advanced thermal reactors currently utilise only about one percent of the energy content of the fuel. Spent fuel reprocessing and recycling of extracted fissile uranium and plutonium in thermal reactors, as several countries already practise, may extend the fuel availability by some 40%. There are a number of efforts underway to improve the energy utilisation rate of the nuclear fuel cycle, even for existing plants. Moreover, there has been a consensus in the nuclear community that development of breeder reactors and plutonium recycling would effectively decouple nuclear power from fuel resource considerations for large-scale development, although there are different opinions about their economic and non-proliferation features.

Table 2 summarises some key challenges that nuclear power faces for a significant (at least ten-fold) increase in capacity in the coming century. In the right column potential technical solutions are indicated.

From Table 2 we can see that actually all the challenges for large-scale nuclear power development may be addressed through technology development. This is a big priority for nuclear power. The main question for nuclear power is how to address the above challenges while at the same time improving economic attractiveness.

Status of Innovative R&D Activities

Technological development is taking place within three general categories:

- Currently operating commercial facilities — improvements in maintenance, operations, engineering support, fuel supply, etc.
- Evolutionary designs — improvements in design and operation for near-term future deployment, involving moderate changes from currently operating commercial facilities.
- Innovative designs — advances in design and operation involving major departures from currently operating commercial facilities for long-term future deployment.

The first two categories of developments are critical, particularly for the next two decades, in order to keep nuclear power alive while more dramatic innovations are prepared. This bridging effort based on existing evolutionary designs is crucial, and will define the future of nuclear power in the first instance. The subsequent generation of reactors and fuel cycles that must form the basis for a large-scale expansion of nuclear power worldwide must depend on innovations in nuclear technology.

The need for innovative R&D has been recognised by the nuclear industry and by those countries that believe in the overall benefits, viability and importance of nuclear power for the long term. Currently, R&D on innovative nuclear fuel cycle and reactor concepts is being performed in Argentina, Canada, China, France, India, Italy, Japan, Republic of Korea, Russia, South Africa, and the USA. The USA embarked on a Nuclear Energy Research Initiative in 1999 to develop advanced reactor and fuel cycle concepts and scientific breakthroughs in nuclear technology to overcome obstacles to the expanded use of nuclear energy.[7]

As an example, attention in some of the above countries has focused on development of small reactors which have various combinations of relative simplicity of design, economy of mass production, and reduced siting costs.[8] Table 3 shows some examples of small reactors under development. The list is not complete. There are many other designs, most of them still at the conceptual level.

There are differences of opinion about the commercial potential of small reactors. Some consider that the main objective of development of small reactors is to increase the potential use of nuclear energy, for electricity or for desalination, in remote areas or where fossil fuel costs are high. These parties assume that small reactors will not be able to compete with large-scale evolutionary reactors, that they will complement them in additional areas where large-scale reactors are not suitable for use. Examples of these types of small reactor designs are KLT-40 and SMART.

Others believe that a breakthrough is possible in the cost of baseload electricity from small reactors, and that they will compete with large-scale NPPs and even gas-fired generation. These parties cite as examples the PBMR and the Carem-25. On-site construction with factory built structures and components, including complete modular units for fast installation, are some of the intended features of these reactors. It is also expected that these will be easier to finance and suitable for deployment even in regions with modest electricity grids.

From early in the development of nuclear power in the 1960s, the closed fuel cycle scheme with breeder reactor was perceived as the best option for large-scale nuclear energy deployment. However, technological breakthroughs over a range of reactors and a range of reactor characteristics are now needed to cope with emerging issues such as non-proliferation, environmental mitigation, economics, and enhanced safety and security needs. Many countries with nuclear power programmes have dealt with these issues at least at the technical level, and have moreover set out new programmes for innovative nuclear fuel cycles.[9]

Desirable features of innovative nuclear fuel cycles can be listed as:

- economic competitiveness;
- reduction of nuclear waste and the hazards associated with its long-term storage;
- furtherance of non-proliferation aims, namely that nuclear materials cannot be easily acquired or readily converted for non-peaceful purposes;
- improved efficiency in resource use.

Table 4 gives examples of recent work in innovative nuclear fuel cycles. Although no large-scale programmes on innovative nuclear fuel cycles are being implemented at present, some countries are investigating the necessary steps for change in the current situation.

After this brief overview of the main challenges nuclear power faces and the main on-going R&D in the area of innovative reactor design and fuel cycle technologies, we can consider the question: "Are the scope and the rate of current R&D efforts enough to develop by 2010–20 some demonstration reactor and fuel cycle systems that could become a basis for a large-scale revival of nuclear power?" In my understanding today this is a very important question and a task for the nuclear community in the coming years. The IAEA is considering how to contribute to addressing this task.

International Cooperation and the role of the IAEA

The IAEA has for more then forty years served "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world and to ensure, so far 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 Agency's on-going activities on innovative reactor and fuel cycle technologies include the activities of several international working groups and coordinated research projects. Furthering international cooperation has always been understood to constitute one of the main areas of activities where the Agency can be of benefit to its member states.

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

Taking into account the above, the Agency is establishing a task force on innovative nuclear reactors and fuel cycles. In order to finalise the scope and objectives of the proposed task force, and to define the human and financial resources necessary to sustain it, the IAEA secretariat will convene a meeting of senior officials in Vienna in November 2000.

The secretariat's initial proposal, which will be further elaborated upon during the November meeting, is that the task force proceed on two tracks:

- The first track will involve a global assessment of the user requirements for future reactors and fuel cycles in order to have a better understanding of the demand and potential for the application of innovative reactors and fuel cycles.
- The second track will involve a compilation and review of technical features and characteristics of innovative reactor and fuel cycles that could meet projected requirements and demand.

The task force might also make recommendations about follow-up actions the Agency and member states may consider, including ways to facilitate information exchange and cooperative research and development among countries working on similar design concepts, to stimulate the pooling of resources and expertise.

REFERENCES

1. *Nuclear Technology Review 2000*. GOV/INF/2000/5/part 1, IAEA.
2. IAEA PRIS Database as of 1 January 2000.
3. *Mitigation of Climate Change, Special Report on Emission Scenarios*. IPCC Working Group III, Intergovernmental Panel on Climate Change, 2000.
4. Kagramanian VS, Kononov SL & Rogner HH, "Nuclear Energy in the New IPCC Emission Scenarios". *IAEA Bulletin* vol 42, no 2, 2000.
5. Majumdar D, Kupitz J, Rogner HH, Shea T, Niehaus F & Fukuda K, "The Need for Innovation". *IAEA Bulletin*, vol 42, no 2, 2000.
6. *Basic Safety Principles for Nuclear Power Plants* (INSAG-12). 75-INSAG-3 rev 1, IAEA, 1999.
7. Magwood WD, *US Department of Energy Generation IV Nuclear Power Systems.* ANS Meeting, 16 November 1999.
8. Mourogov VM & Kupitz J, *Nuclear Energy Issues and the Role of Small and Medium Sized Reactors.* Proceedings of the Twenty-Third Annual Symposium of Uranium Institute, London, September 1998.

9. Fukuda K, Bonne A & Mourogov VM, *Global View on Nuclear Fuel Cycle – Challenges for the 21st Century*. Proceedings of the International Conference on Future Nuclear Systems Global'99, Jackson Hole, Wyoming, USA.

Table 1. World regional distribution of nuclear power plants (from Reference 2).

Region	No. of reactors	Total capacity (MWe)	Total operating experience* (years)
Western Europe	150	126 094	3843
North America	118	107 143	2875
Eastern Europe	68	45 309	1277
East Asia	78	63 732	1193
Middle East & South Asia	12	2 022	197
Latin America	5	2 921	76
Africa	2	1 842	30
World total	433	349 063	9491

*Including experience with shut down reactors; rounded to full years.

Table 2. Large-scale nuclear power development — key challenges and potential technical responses.

Challenges	Availability of a technological response
Safety area: Eliminate severe core damage.	Reactor and nuclear power plant designs based on maximum use of passive safety features.
Waste management: Minimise the volume and toxicity of nuclear waste.	Multi-recycling of most dangerous long-lived radioactive elements in reactors with fast neutron spectrum.
Non-proliferation: Furtherance of non-proliferation aims, namely that nuclear materials cannot be easily acquired or readily converted for non-peaceful purposes.	Recycling of fissile materials, together with radioactive minor actinides; integral nuclear fuel cycle without the stockpiling of Pu.
Resource base: Increase the resource base more than ten fold.	Multi-recycling of plutonium in fast reactors.

Table 3. Examples of smaller reactors under development.

Reactor	Capacity/type	Developer/country
Carem-25	25 MWe PWR	INVAP/Argentina
Floating KLT-40	40 MWe PWR	OKBM/Russian Fed.
PBMR	114 MWe HTR	Eskom/South Africa
SMART	100 MWe PWR	KAERI/Rep of Korea

Table 4. Innovative technologies related to nuclear fuel cycle.

Attribute	Process & system	Relevant countries	Features
Fuel composition & process	Pyro-process	Japan, Russia, USA	Nuclear waste volume is smaller and process facility is simpler than those of wet process (expected economic and environmental advantages).
	Vibro-packed fuel	Russia, Switzerland	Fuel particle is directly produced from acid solution from reprocessing (economic merit is expected compared to powder technology).
	DUPIC system	Canada, Rep. of Korea	Plutonium is not separated from PWR spent fuel (proliferation resistance is expected).
	Thorium fuel (Th–U, Th–Pu)	India, USA	Th resource is abundant. Fuel with Th–^{233}U composition generates less MA than U–Pu fuel.
	Inert-matrix fuel	France, Japan, Switzerland	Due to chemically stable oxide, spent fuel is regarded as waste form (environmental mitigation).
Partitioning and Transmutation (P–T) system	Accelerator Driven System	France, Japan, USA	High neutron energy produced in accelerator destroys MA, LLFP. Sub-critical core enhances safety.
	P–T system with fast reactor (FR)	Japan, Russia	Existing FR technology is applied for destruction of MA, LLFP.
Fast reactor and fuel cycle system	Pb (+Bi) FR	Russia	Enhanced resource utilisation, proliferation resistance, safety and waste features.