Fuelling Innovation

Countries look to the next generation of nuclear power

by Judith Perera

The past few years have seen several multinational initiatives looking at the prospects for the medium- and long-term development of nuclear energy. These include: the US-led Generation IV International Forum (GIF), the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), and the European Michelangelo network for competitiveness and sustainability of nuclear energy in the EU (Micanet). There have also been two major studies — a joint investigation by the IAEA together with the OECD's International Energy Agency (IEA) and Nuclear Energy Agency (NEA), *Innovative Nuclear Reactor Development; Opportunities for International Co-operation;* and an interdisciplinary study by the Massachusetts Institute of Technology (MIT) on *The Future of Nuclear Energy.*

All these cover much of the same ground, looking at innovative nuclear systems including reactors and fuel cycles. But, while they were prompted by the same set of underlying imperatives, they also differ to some extent, not least in the importance they attach to the nuclear fuel cycle. GIF and INPRO are two initiatives where enhanced international co-operation could emerge.

GIF Initiative

GIF is essentially a US initiative. In 1997, the President's Committee of Advisors on Science and Technology reviewed national energy R&D and drew up a programme to address energy and environmental needs for the next century. This noted the importance of assuring a viable nuclear energy option to help meet future energy needs including properly focused R&D to address the principal obstacles to achieving this option including spent nuclear fuel, proliferation, economics, and safety. In response the US Department of Energy (DOE) initiated the Nuclear Energy Research Initiative (NERI) to address technical and scientific issues affecting the future use of nuclear energy in the US. In 1998, DOE established the independent Nuclear Energy Research Advisory Committee (NERAC) to provide advice to the Secretary and to the Director, Office of Nuclear Energy, Science, and Technology (NE), on the DOE civilian nuclear technology programme.

INPRO Members	BOTH INPRO & GIF	GIF Members
Argentina	Argentina	Argentina
Brazil	Brazil	Brazil
Bulgaria	Canada	Canada
Canada	France	France
China	Republic of Korea	Japan
Czech Republic	South Africa	Republic of Korea
France	Switzerland	South Africa
Germany	**Organisational Member:**	Switzerland
India	European Commission	United Kingdom
Indonesia		United States
Republic of Korea		**Organisational Members:**
The Netherlands		FORATOM
Pakistan		European Commission
Russian Federation		
South Africa		
Spain		
Switzerland		
Turkey		
Organisational Member:		
European Commission		

INPRO status as of June 2004. Observers from Euratom, the IAEA, and the Nuclear Energy Agency participate in GIF meetings.

GIF focuses on the collaborative development and demonstration of one or more fourth generation nuclear energy systems that could offer advantages in economics, safety and reliability, sustainability, and could be deployed commercially by 2030. The aim is to share expertise, resources, and test facilities to improve efficiency and avoid duplication. *(See table for GIF members.)*

The National Energy Policy (NEP), issued in May 2001 by the Vice President's National Energy Policy Development Group, supports the expansion of nuclear energy as a major component necessary to meet growing US energy requirements. In September 2002 the NERAC Subcommittee on Generation IV Technology Planning issued the Technology Roadmap for Generation IV Nuclear Energy Systems. In coordination with GIF, six innovative reactor concepts were selected for further collaborative research and development with the supporting fuel cycles a1nd also to serve as focus areas for innovative NERI-sponsored R&D projects. They include:

- Gas-Cooled Fast Reactor (GFR) — a fast-neutron-spectrum, helium-cooled reactor and closed fuel cycle;
- Very-High-Temperature Reactor (VHTR) — a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle;
- Supercritical-Water-Cooled Reactor (SCWR) — a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water;

◗ Sodium-Cooled Fast Reactor (SFR) — a fast-spectrum, sodium-cooled reactor and closed fuel cycle for efficient management of actinides and conversion of fertile uranium;

◗ Lead-Cooled Fast Reactor (LFR) — a fast-spectrum lead of lead/bismuth eutectic liquid metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides;

◗ Molten Salt Reactor (MSR) — produces fission power in a circulating molten salt fuel mixture with an epithermal-spectrum reactor and a full actinide recycle fuel cycle.

They are expected to be deployable within the next three decades. Comparative advantages include reduced capital cost, enhanced nuclear safety, minimal generation of nuclear waste, and further reduction of the risk of weapons materials proliferation. Work has started on four of the selected systems. The goals set for Generation IV nuclear energy systems are:

◗ Sustainability: meet clean air objectives and promote long-term availability of systems and effective fuel utilization for worldwide energy production; minimise and manage nuclear waste and reduce long-term stewardship;

◗ Economics: offer life-cycle cost advantage over other energy sources; offer level of financial risk comparable to other energy projects;

◗ Safety and Reliability: excel in safety and reliability; have a very low likelihood and degree of reactor core damage; eliminate the need for offsite emergency response;

◗ Proliferation Resistance and Physical Protection: represent a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

GIF studies have defined four classes of nuclear fuel cycle including once through, with partial recycle of plutonium, with full plutonium recycle, and with full recycle of transuranic elements. These were modelled over a century based on nuclear energy demand projections developed by the World Energy Council and the International Institute for Applied Systems Analysis.

The once-through cycle was shown to be the most uranium resource-intensive generating the most waste in the form of spent fuel, but the wastes produced are still small compared with other energy technologies. Uranium resources are sufficient to support a once-through cycle at least until mid-century. However, the limiting factor is the availability of repository space. This becomes an important issue, requiring new repository development in a few decades. In the longer term, beyond 50 years, uranium resource availability also becomes a limiting factor.

Systems that employ a fully closed fuel cycle can reduce repository space and performance requirements, although costs must be held to acceptable levels. Closed fuel cycles permit partitioning of nuclear waste and management of each fraction with the best strategy. Advanced waste management strategies include transmutation of selected nuclides, cost effective decay-heat management, flexible interim storage, and customised waste for specific geologic repository environments. They also promise to reduce the long-lived radiotoxicity of waste destined for geological repositories by at least an order of magnitude by recovering most of the heavy long-lived radioactive elements.

Various reactors could also be combined in symbiotic fuel cycles including combinations of thermal and fast reactors. Actinides from the thermal systems can be recycled into fast systems, reducing actinide inventories worldwide. Improvements in the burn-up capability of gas- or water-cooled thermal reactors may also contribute to actinide management in a symbiotic system. Thermal systems may also develop features, such as hydrogen production in high-temperature gas reactors or highly economical light water reactors as part of an overall system offering a more sustainable future.

GIF studies also found that nuclear energy is unique in the market since its fuel cycle contributes only about 20% of its production cost. They further suggested that adopting a fuel cycle that is advanced beyond the once through cycle may be achievable at reasonable cost.

International Project: INPRO

INPRO was initiated in 2000 in a resolution adopted by IAEA Member States to ensure that nuclear energy will be available, as a sustainable resource, to help to fulfil energy needs in the 21st century. In order for nuclear energy to play a meaningful role in the global energy supply, innovative approaches will be required to address concerns about economic competitiveness, safety, waste and potential proliferation risks. Accordingly, INPRO takes a somewhat longer-term perspective than the other initiatives and is the only one which addresses the problems from the point of view of potential users in developing countries by identifying their specific needs. INPRO defines "users" as including a broad range of groups including investors, designers, plant operators, regulatory bodies, local organisations and authorities, national governments, NGOs and the media as well as end users of energy.

INPRO seeks to bring together all interested IAEA Member States, both technology holders and technology users, to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles. These should use sound and economically competitive technology based — as far as possible — on systems with inherent safety features that minimise the risk of proliferation and any impact on the environment. The aim is to create a process that involves all relevant stakeholders and that will have an impact on, draw from, and complement the activities of existing institutions, as well as ongoing initiatives at the national and international level.

The scope of INPRO covers nuclear reactors and fuel cycle facilities expected to come into operation in the future together with the associated fuel cycles. While INPRO considers a 50-year time scale for the necessary analysis, this does not mean that the technologies will be implemented during this time. However, a mixture of current, evolutionary, and innovative designs is expected to be brought into service and co-exist within this period. INPRO has not yet addressed any specific technologies.

In 2001-2003, under Phase 1A, INPRO produced sets of Basic Principles (BPs), User Requirements (URs) and Criteria to compare different concepts and approaches with respect to the key issues in the debate concerning the future role of nuclear energy — economic competitiveness, safety, waste, proliferation, security and physical protection, and sustainability. It not only focussed on technological requirements but also made recommendations on institutional, legal and various infrastructure issues, mainly in the context of the process of continuous globalisation. This phase ended in June 2003, having established a methodology and guidelines to assess different concepts and approaches.

Phase 1B, which began in July 2003, includes the validation of the INPRO methodology through case studies and examination of innovative nuclear energy technologies made available by Member States. This examination will be performed by members on the basis of BPs, URs, criteria and methodology established during Phase 1A. It will also include preliminary collection of information on innovative reactors and fuel cycles. Six INPRO Member States offered to carry out National Case Studies by applying the INPRO methodology to selected national INS:

- Argentina: CAREM-X system including CAREM reactor and SIGMA fuel enrichment process.
- India: APHWR reactor and fuel cycle including a FBR and an ADS for transmutation of waste.
- Republic of Korea: DUPIC fuel cycle technology.
- Russian Federation: nitride-fuelled BN-800 reactor family and adjacent fuel cycle in the equilibrium state.
- China: Pebble Bed High Temperature Reactor.
- Czech Republic: Molten Salt Reactor (concept chosen by Generation IV International Forum (GIF).

In addition, several teams consisting of individual experts are performing case studies, which cover those technologies not addressed by the National Case Studies, in order to obtain a validation of the Methodology as complete as possible.

Final results of these studies and several case studies will be reported to the 7th meeting of the INPRO Steering Committee in late 2004. Innovative nuclear reactor and fuel cycle concepts will then be assessed against the requirements and criteria selected. Drawing on the results from the first phase, Phase 2 will look at available technologies and the feasibility of starting an international project.

INPRO has hitherto depended on the political, financial and technical support accorded by IAEA Member States (in particular Russia, which provided the major financial support for project), but from 2004 funding is partly included in the IAEA regular budget. *(See table for INPRO members.)*

The key feature of INPRO's methodology is the information it provides about the potential of nuclear energy and the consequences of its use. It takes into account the development options for society and its energy requirements as well as the associated expenditure in terms of effort, resources and time. This will provide INPRO members with a tool to help in identifying and assessing the components needed for a future nuclear energy system, such as reactors, waste processing facilities, fuel fabrication and recycling facilities. It will also assist States to identify the research, development and demonstration (RD & D) required to improve existing components for future application and to develop new components as required.

In the area of economics, INPRO considers four market scenarios covering possible future developments. These are characterised by various levels of globalisation and regionalisation and differing views of economic growth versus environmental constraints. Provided innovative nuclear energy systems (INS) are economically competitive, INPRO believes they can play a major role in meeting future energy needs. But to keep the total unit energy cost competitive, all component costs (capital costs, operation and maintenance, fuel, etc) must be considered and managed. Limits on fuel costs imply limits on the capital and operating cost of fuel cycle facilities, including mines, fuel processing and enrichment, fuel reprocessing and the decommissioning and long-term management of the wastes from these facilities.

Regarding sustainability, INPRO has set two basic principles, one related to the acceptability of environmental effects caused by nuclear energy and the second to the capability of INS to deliver energy in a sustainable manner in the 21st century. Protection of the environment is seen as fundamental, and to be sustainable the system must not run out of important resources (such as fissile/fertile material or water) part way through its intended lifetime. The system should also use them at least as efficiently as acceptable alternatives, both nuclear and non-nuclear.

Regarding safety, INPRO Principles and Requirements are based on extrapolation of current trends and seek to encompass the potential interests of developing countries and countries in transition. For nuclear reactors, the fundamental safety functions are to control reactivity, remove heat from the core, and confine radioactive materials and shield radiation. For fuel cycle installations, they are to control subcriticality and chemistry, remove decay heat from radionuclides, and confine radioactivity and shield radiation. The development of INS should be based on a holistic life cycle analysis taking into account the risks and impacts of the integrated fuel cycle.

The safety of waste management involves different time scales and, in many cases different source terms and pathways, compared with nuclear installations. The existing nine principles already defined by the IAEA for the management of radioactive waste have been adopted by INPRO without modification.

As the demand for electricity is expected to grow mainly in developing countries, INPRO believes particular attention should be paid to these countries. For countries that need only a small number of nuclear power plants it would not be rational to develop a fully capable domestic supply structure. Internationally operated companies could provide most of the necessary infrastructure for the construction and operation of nuclear power systems and could supply a valuable service.

Need for Global Co-operation

There is a general consensus on the need for international efforts to develop new nuclear technologies. Establishing some kind of co-operation between existing projects has been discussed and is progressing.

GIF technology goals and INPRO user requirements have many similar or identical statements relating to economics, safety, environment, fuel cycle and waste, proliferation resistance, and sustainability. Approaches for screening and selecting candidate innovative concepts also appear to be quite similar. However, there are some significant differences:

- GIF is already in the phase of initiating R&D, while INPRO has only just completed formulation of its user requirements;

- GIF mainly addresses the demands of a few industrially-developed countries, while INPRO offers a more in-depth consideration of nuclear power in general, taking into account country and region specifics;

- INPRO is expected to involve a broader spectrum of technology proposals for innovative reactors and nuclear fuel cycles, which would meet the demands of nearly all countries – and not just nuclear stakeholders.

- INPRO also seeks to address issues beyond technological requirements, particularly the possible advantages of international cooperation in establishing the necessary infrastructure for individual countries, as well as innovations in legal and institutional structures. INPRO is ready to consider the needs of developing countries in this regard.

- GIF limits its consideration to separate nuclear energy systems with reactors of different types and accompanying fuel cycles.

- INPRO considers that the combinations of such systems should be tailored to different scenarios of nuclear power development at national, regional, and global levels.

GIF and INPRO have the basis for closer co-operation since the focus of their efforts is different. GIF members are mainly the holders of technologies and GIF is considering very complex technologies. However, INPRO sees Asia as the future market for nuclear, including developing countries, where more simple but reliable systems are needed. INPRO includes members from developing countries and so can better understand their needs and requirements.

The role of innovation as a crucial factor to the future of nuclear was highlighted at the IAEA's International Conference on Innovative Technologies for Nuclear Fuel Cycles and Nuclear Power held in Vienna in June 2003. The chairman of India's Atomic Energy Commission, Dr. Anil Kakodkar, stressed the importance of nuclear as part of a diversified energy mix. However, he said there was an underlying conflict between the developing and developed world concerning nuclear power. Many developing countries believed that non-proliferation measures had been used largely to prevent a meaningful technology transfer, he said.

At the IAEA General Conference in September 2003, States adopted a resolution stressing the need for international collaboration in developing innovative nuclear technology and high potential and added value that could be achieved through collaborative efforts. It also stressed the importance of identifying synergies with other international initiatives on innovative nuclear technology development.

It is clear that a more collaborative multinational approach is evolving, though some obstacles remain to be resolved. As developments unfold, co-ordination between INPRO and GIF could soon begin.

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