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International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

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The IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) : Status, Ongoing Activities and Outlook

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Abstract – *The IAEA General Conference (2000) invited “all interested Member States to combine their efforts under the aegis of the IAEA in considering the issues of the nuclear fuel cycle, in particular by examining innovative and proliferation-resistant nuclear technology”. In response to this invitation, the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). The overall objectives of INPRO are to help to ensure that nuclear energy is available to contribute in fulfilling energy needs in the 21st century in a sustainable manner, and to bring together 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. In order to fulfil these objectives, the first phase of INPRO dealt with the development of a methodology to assess and compare the performance of innovative nuclear energy systems. This methodology includes the definition of a set of Basic principles, User requirements and Criteria to be met in different areas (Economics, Sustainability and environment, Safety of nuclear installations, Waste management and Proliferation resistance). The result of this phase was presented in a IAEA document (IAEA-TECDOC-1362, Guidance for the evaluation of innovative nuclear reactors and fuel cycles) issued in June 2003.*

In the present phase of the project, case studies are being carried out in order to validate and improve the developed methodology and the defined set of Basic principles, User requirements and Criteria.

This paper shortly summarizes the results published in IAEA-TECDOC-1362 and the ongoing actions related to case studies. Finally, an outlook of INPRO activities is presented.

I. INTRODUCTION

Existing scenarios for global energy use project that demand will at least double over the next 50 years. Electricity demand is projected to grow even faster. These scenarios suggest that the use of all available generating options, including nuclear energy, will inevitably be required to meet those demands.

In order for nuclear energy to play a meaningful role in the global energy supply in the foreseeable future, innovative approaches will be required to address concerns about economic competitiveness, sustainability and environment, safety, waste management and potential proliferation risks. Considering these requirements and the future scenarios, the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles, referred to as INPRO, following resolutions of the IAEA General Conference.

The overall objectives of INPRO are :

- To help to ensure that nuclear energy is available to contribute in fulfilling, in a sustainable manner, the energy needs in the 21st century.
- To bring together all interested 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 that use sound and economically competitive technology, are based – to the extent possible – on systems with inherent safety features and minimize the risk of proliferation and the impact on the environment.

- To create a process that involves all relevant stakeholders 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.

In order to fulfil these objectives, the first phase of the project (Phase 1A) was dedicated to the definition of requirements, called Basic Principles, User Requirements and Criteria, that innovative nuclear energy systems should meet in five subject areas (Economics, Sustainability and environment, Safety of nuclear installations, Waste management and Proliferation resistance), and to the development of a methodology, referred to as INPRO Methodology, to assess innovative nuclear energy systems on a national, regional and/or global basis.

The result of Phase 1A was presented in a IAEA document : IAEA-TECDOC-1362, Guidance for the evaluation of innovative nuclear reactors and fuel cycles[1].

In the present phase of the project (Phase 1B), several case studies are carried out in order to validate and improve the defined set of Basic Principles, User Requirements and Criteria and the INPRO Methodology, by applying them to the assessment of different technologies.

Upon successful completion of the first phase, a second phase of INPRO may be initiated. It should be directed to identify technologies appropriate for implementation by Member States and examine the feasibility of commencing international projects related to them.

As of January 2004, INPRO has 17 Member States : Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Indonesia, Republic of Korea, Pakistan, Russian Federation, South Africa, Spain, Switzerland, The Netherlands, Turkey and the European Commission.

II. NUCLEAR POWER PROSPECTS AND POTENTIALS

Worldwide there were 441 operating nuclear power plants at the end of 2002 supplying 16 percent of global electricity generation, and cumulative operating experience stood at over 10,000 reactor-year.

The global demand for energy is expected to increase significantly over the next 50 to 100 years, driven in large part by population growth and the desire of developing countries to improve their standard of living.

In 1996 the Inter-governmental Panel on Climate Change (IPCC) commissioned a Special Report on Emission Scenarios (SRES)[2] to replace long-term reference emission scenarios first formulated in 1992. The SRES presented 40 reference scenarios extending to 2100. None of those 40 scenarios included policies designed to avoid or mitigate climate change.

Global primary energy use in the SRES scenarios grows between 1.7 and 3.7-fold between 2000 and 2050. Electricity demand grows almost 8-fold in the high economic growth scenarios, while the median increase is by a factor of 4.7 .

Most of the scenarios include substantial increases in the use of nuclear power. Projections for 2050 range between current capacity levels of 350 GW(e) up to more than 5000 GW(e), with a median of more than 1500 GW(e) (Figure 1). These projected growth levels would require added nuclear power capacity of 50-150 GW(e) per year, even without any policies to reduce GHG emissions.

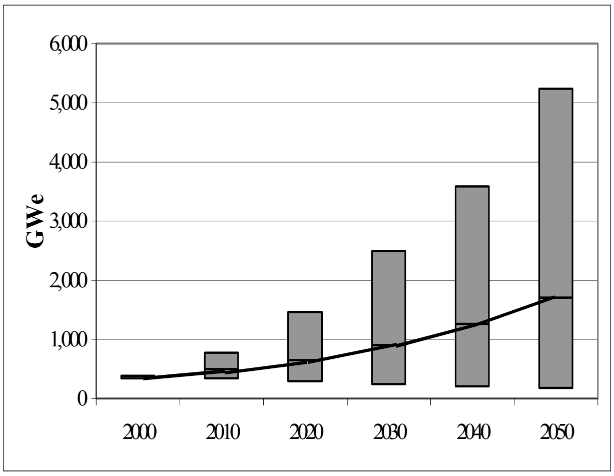


Figure 1 : Range of nuclear power in SRES scenarios, 2000-2050 (Solid line represents median)

Nuclear energy can play an important role in meeting the expanding world energy demand, consistent with the principle of sustainable development. But to do so, nuclear energy and, in particular, innovative nuclear energy systems to be deployed in the 21st century, must be economically competitive with alternatives, must be safe, must be environmentally benign, and concerns about nuclear proliferation must be addressed.

III.DEFINITIONS OF SELECTED TERMS WITHIN INPRO

Nuclear Energy System : comprises the complete spectrum of nuclear facilities and associated institutional measures. Nuclear facilities include facilities for: mining and milling, processing and enrichment of uranium and/or thorium, manufacturing of nuclear fuel, production (of electricity or other energy supply), reprocessing of nuclear fuel, and facilities for related materials management activities, including transportation and waste management. All phases in the life cycle of such facilities are included, such as site acquisition, design, construction, commissioning, operation, decommissioning and site release/closure. Institutional measures consist of agreements, treaties, national and international legal frameworks and conventions, and the national and international infrastructure needed to operate a nuclear program.

Innovative Nuclear Energy Systems (INS) : refers to systems that will position nuclear energy to make a major contribution to global energy supply in the 21st century. In this context, future systems may include evolutionary as well as innovative designs. An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining design proveness to minimize technological risks. An innovative design is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice.

Within INPRO the demands on INS are structured in a hierarchical order :

Basic Principles : the highest level in the INPRO structure is a Basic Principle**,** which is a statement of a general rule that provides broad guidance for the development of an INS.

User Requirements : the second level in the INPRO hierarchy is called a User Requirement. These are derived form the Basic Principles, and are the conditions that must be met to achieve Users' acceptance of a given INS. A User is any entity that has a stake or interest in potential applications of nuclear technologies (designers, investors,. power generators and utilities, national governments, end users of energy, etc..).

Criteria : are required to determine whether and how well a given User Requirement is being met. A Criterion includes an *Indicator* and an *Acceptance Limit*. Indicators may be based on a single parameter, on an aggregate variable, or a status statement. An Acceptance Limit is a target, either qualitative or quantitative, against which the value of an Indicator can be compared leading to a judgement of acceptability (pass/fail, good /bad, better/poorer).

The relationship between the Basic Principle, the User Requirement and the Criterion is, thus, as follows :

- The fulfilment of a Basic Principle is achieved by meeting the related User Requirement(s).
- The fulfilment of a User Requirement is confirmed by the Indicator(s) complying with the Acceptance Limit(s) of the corresponding Criterion (Criteria).

A clear example of this hierarchical order can be taken from the structure of the safety area :

Basic Principle : Innovative nuclear reactors and fuel cycle installations shall incorporate enhanced defence-in-depth.
User Requirement : Innovative nuclear reactors and fuel cycle installations shall not need relocation or evacuation measures outside the plant site.
Criterion :
Indicator : Probability of large release of radioactivity to the environment.
Acceptance Limit : $<10^{-6}$ plant*year, or excluded by design.

IV. BASIC PRINCIPLES, USER REQUIREMENTS AND CRITERIA DEFINED BY INPRO

IV.A. Economics

In the area of Economics four selected scenarios from the SRES study have been analyzed (Figure 2). They cover a variety of possible future developments that are characterized by differing levels of globalization and regionalization and by differing views of economic growth versus environmental constraints.

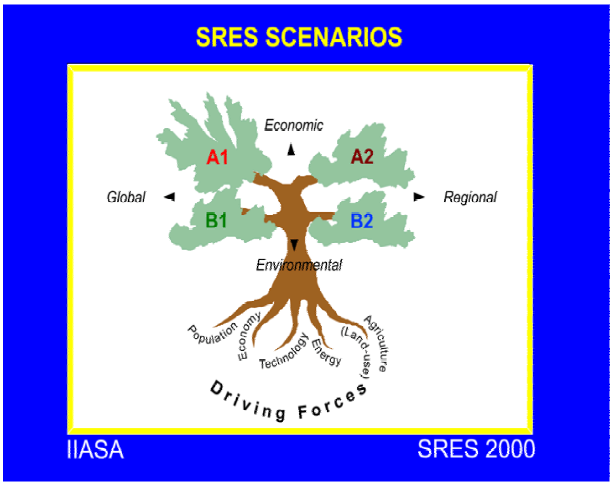
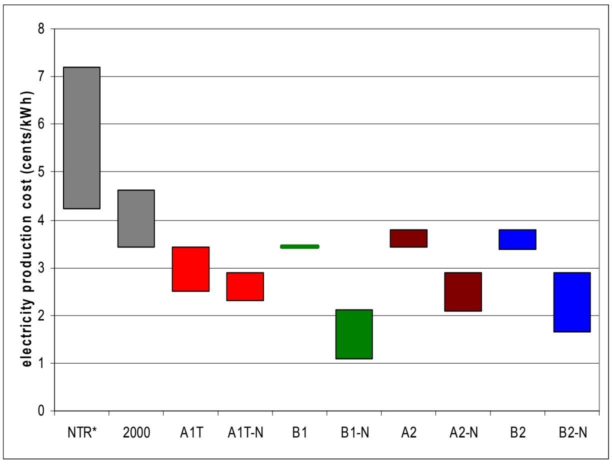


Figure 2 : SRES scenarios used in INPRO

Provided INS are economically competitive they can play a major role in meeting future energy needs. Economic competitiveness depends on the learning rates (cost reduction as a function of experience) achieved by nuclear energy relative to those of competing technologies. Specific capital costs and electricity production costs (Figure 3) have been derived, which are indicative of costs that would enable nuclear energy to compete successfully against alternative energy sources for the four marker scenarios chosen.



NTR* : Nuclear Technology Review (IAEA)
2000 : SRES input in the year 2000
Figure 3 : Ranges for electricity production cost in 2050 for nuclear power plants

The important message is that for nuclear technology to gain and grow market share it must benefit sufficiently from learning to keep it competitive with competing energy technologies. For such learning to take place experience must be gained.

INPRO defined two Basic Principles, five User Requirements and several Criteria in the area of Economics. Table I shows the defined Basic Principles.

Table I : Basic Principles for Economics

Basic Principle 1 : *The cost of energy from innovative nuclear energy systems, taking all costs and credits into account, must be competitive with that of alternative energy sources.*
Basic Principle 2 : *Innovative Nuclear Energy Systems must represent an attractive investment compared with other major capital investments.*

Basic Principle 1 reflects the fact that, given options, customers will tend to choose the lowest cost option. All life-cycle costs included in the energy system must be accounted for. Choices of energy supply do not depend only on the up-front cost. Other factors associated with competing energy sources, such as safety, environmental impacts and socio-economic benefits, enter into the decision-making process.

As stated in Basic Principle 2, the development and deployment of INS requires investment, so investors must be convinced that INS represent a wise investment. The Internal Rate of Return (IRR) and the Net Present Value (NPV) must be attractive compared with investments in competing energy technologies. Private sector investors will be attracted by a competitive IRR, while Net Present Value analysis, which can take into account all benefits such as security of energy supply and technology development is of more interest to government investors.

IV.B. Sustainability and Environment

There exists international and strong interest and support for the concept of sustainability, which expresses that the present generation should not compromise the ability of future generations to fulfil their needs. Nuclear power supports sustainable development by providing much needed energy with relative low burden on the atmosphere, water and land use. Further deployment of nuclear power would help to alleviate the environmental burden caused by other forms of energy production, particularly the burning of fossil fuels. Two Basic Principles have been defined in this area (Table II), the first dealing with the acceptability of environmental effects caused by nuclear energy and the second dealing with the efficient use of non-renewable resources. Derived from those Basic Principles, four User Requirements and several corresponding Criteria were defined.

Table II : Basic Principles for Sustainability and Environment

Basic Principle 1 : *The expected (best estimate) adverse environmental effects of the INS must be well within the performance envelope of current nuclear energy systems delivering similar energy products.*
Basic Principle 2 : *The INS must be capable of contributing to energy needs in the future while making efficient use of non-renewable resources.*

Protection of the environment from harmful effects is seen to be fundamental to sustainability. Adherence to this principle requires that the future must be left with a healthy environment. Nevertheless the major environmental advantages of nuclear technology in meeting global energy needs, the potential adverse effects that the various components of the nuclear fuel cycle may have on the environment must be prevented or mitigated effectively to make nuclear energy sustainable in the long term. Environmental effects include : physical, chemical or biological changes in the environment; health effects on people, plants and animals; effects on quality of life of people; etc.. Both radiological and non-radiological effects as well as trade-offs and synergies among the effects form different system components and different environmental stressors need to be considered.

To be sustainable the system must not run out of important resources part way through its intended lifetime. These resources include fissile/fertile materials, water and other critical materials. The system should also use them at least as efficiently as acceptable alternatives, both nuclear and non-nuclear.

All relevant factors (sources, stressors, pathways, receptors and endpoints) must be accounted for in the analysis of the environmental effects of a proposed energy system, and the environmental performance of a proposed technology needs to be evaluated as an integrated whole by considering the likely environmental effects of the entire collection of process, activities and facilities in the energy system at all stages of its life cycle.

IV.C. Safety of Nuclear Installations

There is a worldwide consensus on the General Nuclear Safety Objective[3] : "To protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards".

Derived from this objective, the fundamental safety functions for nuclear reactors are to : control reactivity, remove heat from core, confine radioactive materials and shield radiation. For fuel cycle installations, the safety functions are to : control sub-criticality and chemistry, remove decay heat from radionuclides, confine radioactivity and shield radiation.

To ensure that INS will fulfil the fundamental safety functions, INPRO has defined five Basic Principles (Table III) and derived from them twenty seven User Requirements and several Criteria.

Table III : Basic Principles for Safety of Nuclear Installations

Basic Principle 1 : *INS installations shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and the levels of protection in defence-in-depth shall be more independent form each other than in current installations.*
Basic Principle 2 : *INS installations shall prevent, reduce or contain releases (in that order of priority) of radioactive and other hazardous material in construction, decommissioning and accidents to the point that these risks are comparable to that of industrial facilities used for similar purposes.*
Basic Principle 3 : *INS installations shall incorporate increased emphasis on inherent safety characteristics as a part of their fundamental safety approach.*
Basic Principle 4 : *INS installations shall include associated RD&D work to bring the knowledge of plant characteristics and the capability of computer codes used for safety analyses to at least the same confidence level as for the existing plants.*
Basic Principle 5 : *INS facilities shall include a holistic life-cycle analysis encompassing the effect on people and on the environment of the entire integrated fuel cycle.*

INPRO expects that INS will incorporate enhanced defence-in-depth as part of their basic approach to safety, but with more independence of the different levels of protection in the defence-in-depth strategy, and with an increased emphasis on inherent safety characteristics and passive safety features.

The general directions for innovation to enhance the levels of defence-in-depth are presented in Table IV.

Table IV. Innovative direction to enhance the levels of defence-in-depth

Level of defence-in-depth	Objectives[4]	Innovation direction (INPRO)	
1	Prevention of abnormal operations and failures.	Enhance prevention by increased emphasis on inherently safe design characteristics and passive safety features.	More independence of levels from each other
2	Control of abnormal operation and detection of failures.	Give priority to advanced control and monitoring systems with enhanced reliability, intelligence and limiting features.	
3	Control of accidents within the design basis.	Achieve fundamental safety functions by optimised combination of active and passive design features; limit fuel failures; increase grace period to several hours.	
4	Control of severe plant conditions, including prevention and mitigation of the consequence of severe accidents.	Increase reliability of systems to control complex accident sequences; decrease severe core damage frequency by at least one order of magnitude, and even more for urban-sited facilities.	
5	Mitigation of radiological consequences of significant releases of radioactive materials.	No need for evacuation or relocation measures outside the plant site.	

The end point should be the prevention, reduction and containment of radioactive releases to make the risk of INS comparable to that of industrial facilities used for similar purposes so that for INS there will be no need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility.

RD&D must be carried out before deploying INS to bring the knowledge of plant characteristics and the capability of codes used for safety analyses to the same level as for existing plants. The deployment of INS should be based on a holistic life cycle analysis that takes into account the risks and impacts of the integrated fuel cycle. Safety analyses will involve a combination of deterministic and probabilistic assessments, including best estimate plus uncertainty analysis.

IV.D. Waste Management

The already existing nine principles defined by the IAEA[5] for the management of radioactive waste have been adopted by INPRO without modification (Table V). Thus, waste management is to be carried out in such a way that human health and the environment are protected now and in the future, effects beyond national borders shall be taken into account, undue burdens passed to future generations shall be avoided, waste shall be minimized, appropriate legal frame works shall be established and inter-dependencies among steps shall be taken into account.

Table V : Basic Principles for Waste Management

Basic Principle 1 : *Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.*
Basic Principle 2 : *Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.*
Basic Principle 3 : *Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.*
Basic Principle 4 : *Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.*
Basic Principle 5 : *Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.*
Basic Principle 6 : *Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.*
Basic Principle 7 : *Generation of radioactive waste shall be kept to a minimum practicable.*
Basic Principle 8 : *Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.*
Basic Principle 9 : *The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.*

These principles in turn lead to INPRO requirements to specify a permanently safe end state for all wastes and to move wastes to its end state as early as practical, to ensure that intermediate steps do not inhibit or complicate the achievement of the end state, that the design of waste management practices and facilities be optimised as part of the optimisation of the overall energy system and life cycle, and for assets to cover the costs of managing all wastes in the life cycle to be accumulated to cover the accumulated liability at any stage of the life cycle. It is also expected that prior work carried out by the IAEA in waste management will be used to the extent possible. RD&D is recommended to be carried out in a number of areas including partitioning and transmutation and long term human factors analysis to facilitate assessments of long term risks for waste management systems that require long term institutional controls.

IV.E. Proliferation Resistance

In designing future nuclear energy systems, it is important to consider the potential for such systems being misused for the purpose of producing nuclear weapons. Such considerations are among the key considerations behind the international non-proliferation regime, a fundamental component of which is the IAEA safeguards system. INPRO set out to provide guidance on incorporating Proliferation Resistance into INS. The INPRO results in this area are largely based on the international consensus reached in October 2002 at a meeting held in Como, Italy.

Generally, two types of proliferation resistance measures or features are distinguished : intrinsic and extrinsic. Intrinsic features result from the technical design of INS including those that facilitate the implementation of extrinsic measures. Extrinsic measures are based on States' decisions and undertakings related to nuclear energy systems.

Intrinsic features consist of technical features that : a) reduce the attractiveness for nuclear weapons programmes of nuclear material during production, use, transport, storage and disposal, including material characteristics such as isotopic content, chemical form, bulk and mass, and radiation properties ; b) prevent or inhibit the diversion of nuclear material, including the confining of nuclear material to locations with limited points of access, and materials that are difficult to move without being detected because of size, weight, or radiation ; c) prevent or inhibit the undeclared production of direct-use material, including reactors designed to prevent undeclared target materials from being irradiated in or near the core of a reactor ; reactor cores with small reactivity margins that would prevent operation of the reactor with undeclared targets ; and fuel cycle facilities and processes that are difficult to modify; and d) that facilitate nuclear material accounting and verification, including continuity of knowledge.

Five categories of extrinsic features are defined, as follows : commitments, obligations and policies of states, such as the Treaty on Non-Proliferation of Nuclear Weapons and the IAEA safeguards agreements ; agreements between nuclear material exporting and importing states ; commercial, legal or institutional arrangements that control access to nuclear material and technology ; verification measures by the IAEA or by regional, bilateral and national measures ; and legal and institutional measures to address violations of measures defined above.

INPRO has produced Basic Principles (Table VI) that require : the minimization of the possibilities of misusing nuclear material in INS ; a balanced and optimised combination of intrinsic features and extrinsic measures ; the development and implementation of intrinsic features ; and a clear, documented and transparent method of assessing proliferation resistance.

Table VI : Basic Principles for Proliferation Resistance

Basic Principle 1 : *Proliferation resistant features and measures should be provided in INS to minimize the possibilities of misuse of nuclear materials for nuclear weapons.*
Basic Principle 2 : *Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself.*
Basic Principle 3 : *Extrinsic proliferation resistance measures, such as control and verification measures will remain essential, whatever the level of effectiveness of intrinsic features.*
Basic Principle 4 : *From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged.*
Basic Principle 5 : *Communication between stakeholders will be facilitated by clear, documented and transparent methodologies for comparison or evaluation/assessment of proliferation resistance.*

To comply with these Basic Principles requires the application of the concept of defence-in-depth by, e.g., incorporating redundant and complementary measures ; an early consideration of proliferation resistance in the development and design of INS ; and the utilization of intrinsic features to increase the efficiency of extrinsic measures. RD&D is needed in a number of areas, in particular, in developing a process to assess the proliferation resistance of a defined INS.

In total, INPRO defined five User Requirements and several Criteria in this area.

IV.F. Cross Cutting Issues

Issues other than technical requirements are important to potential users of INS. Many of the factors that will either facilitate or obstruct the on-going deployment of nuclear power over the next fifty years are *Cross Cutting Issues* that relate to nuclear power infrastructure, international cooperation, and human resources. Nuclear power infrastructure comprises all features / substructures that are necessary in a given country for the successful deployment of nuclear power plants including legal, institutional, industrial, economic and social features / substructures. The SRES scenarios indicate that the growth of nuclear power will be facilitated by globalization and internationalization of the world economy, and that the growth of demand in developing countries will be a major consideration. Globalization and the importance of developing countries in future world energy markets point to the need to adapt infrastructures, both nationally and regionally, and to do so in a way that will facilitate the deployment of nuclear power systems in developing countries.

In a globalizing world with a growing need for sustainable energy, harmonization of regulations and licensing procedures could facilitate the application of nuclear technology. Such harmonization among different markets is in the interest of suppliers and developers of technology as well as users and investors. The development of innovative reactors to comply with the Basic Principles, User Requirements and Criteria set out in this project should facilitate such harmonization and could make it possible to change the way the production of nuclear energy is regulated. When, for example, the risks from INS are ‘comparable to that of industrial facilities used for similar purposes,’ and ‘there is no need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility,’ the requirements for licensing could possibly be simplified. In developing countries, and amongst them countries that do not have a highly developed nuclear knowledge base and infrastructure, the development of regional or international licensing and regulatory mechanisms and organizations could play an important role. Additional factors that would be expected to favour the deployment of INS, particularly in developing countries include: optimisation of the overall nuclear energy system by considering component facilities located in different countries as part of an international multi-component system; recognizing the needs of developing countries that have a limited infrastructure and a real but limited need for nuclear energy; vendor countries offering a full-scope service, up to and including the provisions of management and operations.

The life cycle of nuclear power systems, including design, construction, operation, decommissioning, and the waste management, extends well over fifty years in most cases and can easily extend well beyond one hundred years. Thus, a firm long-term commitment of the government and other stakeholders is seen as a requirement for the successful implementation and operation of a nuclear power investment and a condition for public acceptance. Clear communications on energy demands and supply options are important to developing an understanding of the necessity for and the benefits to be obtained from such long-term commitments. A clear enunciation of the potential role of nuclear energy in addressing climate change concerns in a sustainable and economic manner, together with the performance of existing plants can play an important role in such communications.

The development and use of nuclear power technology requires adequate human resources and knowledge. Globalization brings with it the opportunity to draw on a much broader pool of resources rather than striving to maintain a complete domestic capability across the many disciplines of science and engineering that constitute the range of technologies on which nuclear energy systems depend. International cooperation in science and development can assist with optimizing the deployment of scarce manpower and, just as important, the construction and operation of large-scale research and engineering test facilities.

V. INS ASSESSMENT – INPRO METHODOLOGY

INPRO has also developed a methodology for evaluating INS, the INPRO *Methodology*. It comprises the INPRO Basic Principles, User Requirements, and Criteria, and a set of tables and guidance on their use, that can be used to evaluate a given INS, or a component of such a system on a national, regional and/or global basis.

An assessment of how well an INS complies with Basic Principles, User Requirements and Criteria, is a bottom-up process, which starts with the Judgement of the ability to comply with each criterion. The set of defined Judgement values is presented in Table VII.

Table VII. Outcomes of an INS assessment against a defined criterion

Judgment	*Meaning of the Judgment*
Very High Potential to satisfy the Criterion (VHP).	All components (parameters) of the Approach of the INS being assessed have been theoretically demonstrated and, where necessary, experimentally verified and meet the Criterion.
High Potential to satisfy the Criterion (HP).	Not all components (parameters) of the Approach of the INS being assessed have been theoretically demonstrated or experimentally verified, but there is theoretical evidence that this Approach could meet the Criterion.
Potential to satisfy the Criterion (P).	No theoretical or experimental evidence that the Criterion cannot be met, due to some physical, technological or other limitation which cannot be overcome by later technology developments.
No Potential to satisfy the Criterion (NP).	Theoretical or experimental evidence that the Criterion cannot be met by means of technology development due to some physical, technological or other limitation. Explanation should be provided.

An INS is judged to have a Very High Potential to satisfy a given User Requirement when it has Very High Potential to meet all the Criteria linked to this User Requirement. If the Judgement for at least one of the associated Criterion is only High Potential, then the Judgement for this User Requirement is High Potential. A similar logic is applied to determine the Judgement of a Basic Principle, based on the Judgement of the User Requirements associated with it.

Additional factors also enter into the assessment, including the maturity status of the INS. As a step in the INPRO methodology, each technology should be classified into the appropriate category defined below :

Category 1 (Proven): Well demonstrated technologies, successfully used in nuclear energy systems (and/or in other industries), for which there is an established industrial infrastructure, an experimental and technological base, and a reliable set of physical and mathematical models.

Category 2 (Developed): Technologies that have not yet been successfully demonstrated in an actual nuclear energy system, but that are at an advanced stage of development based on extensive analytical and experimental work, and that have been demonstrated in either pilot plant or in large-scale engineering facilities simulating all relevant features of an actual nuclear energy system. The industrial infrastructure to realize the technology on a large scale is considered feasible, though it may not yet exist.

Category 3 (Evolving): Technologies under development, for which demonstration and pilot industrial facilities have been set up, and there is an experimental base and major engineering processes are under way, physical and mathematical models have been developed to a significant extent and are continually improving, but for which there is still no industrial infrastructure.

Category 4 (Conceptual): Technologies proposed for development, for which only individual features and prospects for application have been enunciated so far. In the initial development stages of such technologies it may be possible to "borrow" the experimental databases and mathematical models from other technology options, but it is recognized that, eventually, additional experimental facilities and new mathematical models will be necessary. Time and resources will be needed to establish such facilities and models and to demonstrate the technology.

This information will be useful in assessing the uncertainty to be assigned to the assessment, and in estimating the level of effort required to develop an innovative or evolutionary technology from its current level of development to commercial application.

Additional effort is needed to validate and adjust this methodology. For this purpose, Case Studies are being performed by some INPRO Member States and different teams of international experts.

VI. ONGOING ACTIVITIES

After the completion of Phase 1A, Phase 1B was started in June 2003. In the first part of this phase, case studies are being performed to validate and adjust the INPRO methodology by applying it to the assessment of specific INS. These case studies are evaluating the following :

- Whether the INPRO Basic Principles, User Requirements and Criteria are understandable, workable, consistent, comprehensive and dependent or independent of the system studied.
- Whether the INPRO methodology is useful for providing an overall assessment of the system, for comparing different systems, components and approaches, identifying regional specificities, and for identifying the directions and objectives of RD&D needed for the further development of a given INS.

Four 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.

In addition, several case studies are being performed by individual international experts, covering those technologies not addressed by the National Case Studies, in order to obtain a validation of the Methodology as complete as possible.

After considering the final results of both national and individual case studies, the definitive INPRO Methodology, updated and validated, will be available for realizing the second part of Phase 1B, which is the assessment of selected INS made available by Member States. This assessment will be performed by Member States.

Also during this phase, the Phase 1A Report is being presented to various interest groups, amongst them, nuclear industry representatives and national regulatory authorities. These groups will be involved in the early stages of innovative developments.

VII. OUTLOOK

Upon successful completion of Phase 1B, taking into account advice form the Steering Committee of INPRO, and with the approval of participating Member States, a second phase of INPRO may be initiated. Drawing on the results from the first phase, it will be directed to :

- Examining in the context of available technologies the feasibility of commencing an international project.
- Identifying technologies, which might be appropriate for implementation by Member States of such an international project.

VIII. CONCLUSIONS

The final results of INPRO Phase 1A were presented in a IAEA document published in June 2003. Phase 1A was an important first step toward INPRO's two objectives of (1) ensuring the availability of nuclear energy to contribute to meeting growing global energy needs in the 21st century and (2) bringing together prospective buyers and sellers of nuclear technology, and developing and developed countries, to jointly consider actions needed to accelerate nuclear innovation in directions most likely to be useful to the energy markets of the future.

The 21st century promises the most competitive, globalized markets in human history, the most rapid pace of technological change ever, and the greatest expansion of energy use, particularly in developing countries. For a technology to make a truly substantial contribution to energy supplies, innovation is essential. It will be the defining feature of a successful nuclear industry and a critical feature of international co-operation in support of that industry, cooperation that ranges from joint scientific and technological initiatives, to safety standards and guidelines, and to security and safeguards activities. Innovation is also essential to attract a growing, high-quality pool of talented scientists, engineers and technicians needed to support a truly substantial nuclear contribution to global energy supplies.

To help co-ordinate and guide the development of INS, INPRO Phase 1A has set out initial Basic Principles, User Requirements and corresponding Criteria in the areas of Economics, Environment, Safety, Waste management, and Proliferation resistance. Cross-cutting issues related to infrastructure and international co-operation have also been discussed. A methodology for assessing INS has been created for the use of Member States and independent analysts. It complements and builds upon requirements and criteria set out in existing documents such as the IAEA Safety Standards Series. This output of INPRO, the Phase 1A Report, is expected to be validated and sharpened during the current Phase 1B, based on the feedback from the case studies being performed.

ACKNOWLEDGMENTS

The IAEA highly appreciates the guidance and advice given by INPRO Member States during Steering Committee meetings, and contributions from international experts participating in the consultancies and workshops to complete the INPRO Phase 1A report timely and successfully.

NOMENCLATURE

ADS :	Accelerator Driven System
DUPIC :	Direct Use of spent PWR fuel in CANDU reactors
FBR :	Fast Breeder Reactor
INS :	Innovative Nuclear Energy System
RD&D	Research, development and demonstration

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The IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) : Status, Ongoing Activities and Outlook

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Abstract – *The IAEA General Conference (2000) invited "all interested Member States to combine their efforts under the aegis of the IAEA in considering the issues of the nuclear fuel cycle, in particular by examining innovative and proliferation-resistant nuclear technology". In response to this invitation, the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). The overall objectives of INPRO are to help to ensure that nuclear energy is available to contribute in fulfilling energy needs in the 21st century in a sustainable manner, and to bring together 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. In order to fulfil these objectives, the first phase of INPRO dealt with the development of a methodology to assess and compare the performance of innovative nuclear energy systems. This methodology includes the definition of a set of Basic principles, User requirements and Criteria to be met in different areas (Economics, Sustainability and environment, Safety of nuclear installations, Waste management and Proliferation resistance). The result of this phase was presented in a IAEA document (IAEA-TECDOC-1362, Guidance for the evaluation of innovative nuclear reactors and fuel cycles) issued in June 2003.*

In the present phase of the project, case studies are being carried out in order to validate and improve the developed methodology and the defined set of Basic principles, User requirements and Criteria.

This paper shortly summarizes the results published in IAEA-TECDOC-1362 and the ongoing actions related to case studies. Finally, an outlook of INPRO activities is presented.

I. INTRODUCTION

Existing scenarios for global energy use project that demand will at least double over the next 50 years. Electricity demand is projected to grow even faster. These scenarios suggest that the use of all available generating options, including nuclear energy, will inevitably be required to meet those demands.

In order for nuclear energy to play a meaningful role in the global energy supply in the foreseeable future, innovative approaches will be required to address concerns about economic competitiveness, sustainability and environment, safety, waste management and potential proliferation risks. Considering these requirements and the future scenarios, the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles, referred to as INPRO, following resolutions of the IAEA General Conference.

The overall objectives of INPRO are :

- To help to ensure that nuclear energy is available to contribute in fulfilling, in a sustainable manner, the energy needs in the 21st century.
- To bring together all interested 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 that use sound and economically competitive technology, are based – to the extent possible – on systems with inherent safety features and minimize the risk of proliferation and the impact on the environment.

- To create a process that involves all relevant stakeholders 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.

In order to fulfil these objectives, the first phase of the project (Phase 1A) was dedicated to the definition of requirements, called Basic Principles, User Requirements and Criteria, that innovative nuclear energy systems should meet in five subject areas (Economics, Sustainability and environment, Safety of nuclear installations, Waste management and Proliferation resistance), and to the development of a methodology, referred to as INPRO Methodology, to assess innovative nuclear energy systems on a national, regional and/or global basis.

The result of Phase 1A was presented in a IAEA document : IAEA-TECDOC-1362, Guidance for the evaluation of innovative nuclear reactors and fuel cycles[1].

In the present phase of the project (Phase 1B), several case studies are carried out in order to validate and improve the defined set of Basic Principles, User Requirements and Criteria and the INPRO Methodology, by applying them to the assessment of different technologies.

Upon successful completion of the first phase, a second phase of INPRO may be initiated. It should be directed to identify technologies appropriate for implementation by Member States and examine the feasibility of commencing international projects related to them.

As of January 2004, INPRO has 17 Member States : Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Indonesia, Republic of Korea, Pakistan, Russian Federation, South Africa, Spain, Switzerland, The Netherlands, Turkey and the European Commission.

II. NUCLEAR POWER PROSPECTS AND POTENTIALS

Worldwide there were 441 operating nuclear power plants at the end of 2002 supplying 16 percent of global electricity generation, and cumulative operating experience stood at over 10,000 reactor-year.

The global demand for energy is expected to increase significantly over the next 50 to 100 years, driven in large part by population growth and the desire of developing countries to improve their standard of living.

In 1996 the Inter-governmental Panel on Climate Change (IPCC) commissioned a Special Report on Emission Scenarios (SRES)[2] to replace long-term reference emission scenarios first formulated in 1992. The SRES presented 40 reference scenarios extending to 2100. None of those 40 scenarios included policies designed to avoid or mitigate climate change.

Global primary energy use in the SRES scenarios grows between 1.7 and 3.7-fold between 2000 and 2050. Electricity demand grows almost 8-fold in the high economic growth scenarios, while the median increase is by a factor of 4.7 .

Most of the scenarios include substantial increases in the use of nuclear power. Projections for 2050 range between current capacity levels of 350 GW(e) up to more than 5000 GW(e), with a median of more than 1500 GW(e) (Figure 1). These projected growth levels would require added nuclear power capacity of 50-150 GW(e) per year, even without any policies to reduce GHG emissions.

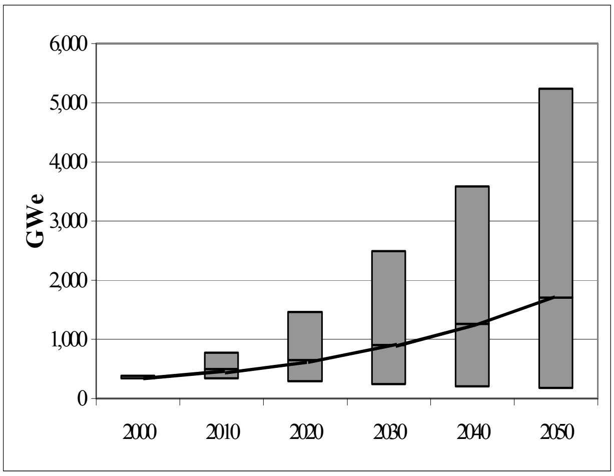


Figure 1 : Range of nuclear power in SRES scenarios, 2000-2050 (Solid line represents median)

Nuclear energy can play an important role in meeting the expanding world energy demand, consistent with the principle of sustainable development. But to do so, nuclear energy and, in particular, innovative nuclear energy systems to be deployed in the 21st century, must be economically competitive with alternatives, must be safe, must be environmentally benign, and concerns about nuclear proliferation must be addressed.

III.DEFINITIONS OF SELECTED TERMS WITHIN INPRO

Nuclear Energy System : comprises the complete spectrum of nuclear facilities and associated institutional measures. Nuclear facilities include facilities for: mining and milling, processing and enrichment of uranium and/or thorium, manufacturing of nuclear fuel, production (of electricity or other energy supply), reprocessing of nuclear fuel, and facilities for related materials management activities, including transportation and waste management. All phases in the life cycle of such facilities are included, such as site acquisition, design, construction, commissioning, operation, decommissioning and site release/closure. Institutional measures consist of agreements, treaties, national and international legal frameworks and conventions, and the national and international infrastructure needed to operate a nuclear program.

Innovative Nuclear Energy Systems (INS) : refers to systems that will position nuclear energy to make a major contribution to global energy supply in the 21st century. In this context, future systems may include evolutionary as well as innovative designs. An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining design proveness to minimize technological risks. An innovative design is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice.

Within INPRO the demands on INS are structured in a hierarchical order :

Basic Principles : the highest level in the INPRO structure is a Basic Principle**,** which is a statement of a general rule that provides broad guidance for the development of an INS.

User Requirements : the second level in the INPRO hierarchy is called a User Requirement. These are derived form the Basic Principles, and are the conditions that must be met to achieve Users’ acceptance of a given INS. A User is any entity that has a stake or interest in potential applications of nuclear technologies (designers, investors,. power generators and utilities, national governments, end users of energy, etc..).

Criteria : are required to determine whether and how well a given User Requirement is being met. A Criterion includes an *Indicator* and an *Acceptance Limit*. Indicators may be based on a single parameter, on an aggregate variable, or a status statement. An Acceptance Limit is a target, either qualitative or quantitative, against which the value of an Indicator can be compared leading to a judgement of acceptability (pass/fail, good /bad, better/poorer).

The relationship between the Basic Principle, the User Requirement and the Criterion is, thus, as follows :

- The fulfilment of a Basic Principle is achieved by meeting the related User Requirement(s).
- The fulfilment of a User Requirement is confirmed by the Indicator(s) complying with the Acceptance Limit(s) of the corresponding Criterion (Criteria).

A clear example of this hierarchical order can be taken from the structure of the safety area :

Basic Principle : Innovative nuclear reactors and fuel cycle installations shall incorporate enhanced defence-in-depth.

User Requirement : Innovative nuclear reactors and fuel cycle installations shall not need relocation or evacuation measures outside the plant site.

Criterion :

Indicator : Probability of large release of radioactivity to the environment.

Acceptance Limit : $<10^{-6}$ plant∗year, or excluded by design.

IV. BASIC PRINCIPLES, USER REQUIREMENTS AND CRITERIA DEFINED BY INPRO

IV.A. Economics

In the area of Economics four selected scenarios from the SRES study have been analyzed (Figure 2). They cover a variety of possible future developments that are characterized by differing levels of globalization and regionalization and by differing views of economic growth versus environmental constraints.

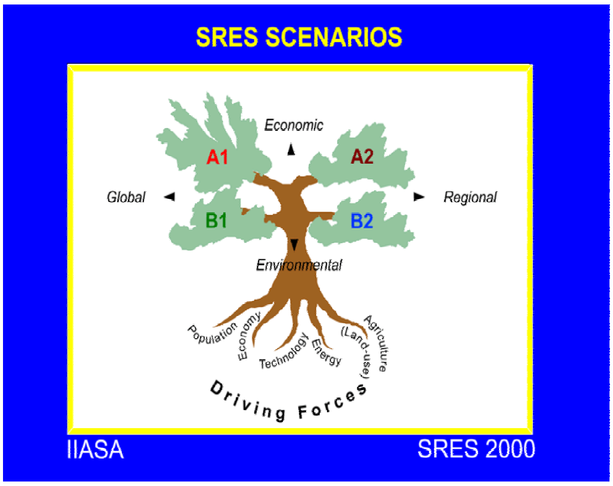
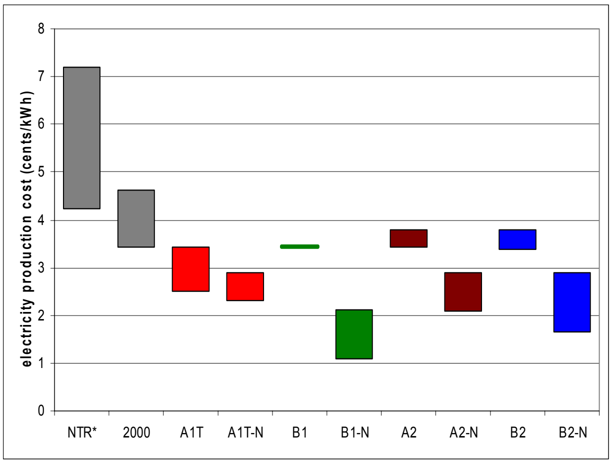


Figure 2 : SRES scenarios used in INPRO

Provided INS are economically competitive they can play a major role in meeting future energy needs. Economic competitiveness depends on the learning rates (cost reduction as a function of experience) achieved by nuclear energy relative to those of competing technologies. Specific capital costs and electricity production costs (Figure 3) have been derived, which are indicative of costs that would enable nuclear energy to compete successfully against alternative energy sources for the four marker scenarios chosen.



NTR* : Nuclear Technology Review (IAEA)
2000 : SRES input in the year 2000
Figure 3 : Ranges for electricity production cost in 2050 for nuclear power plants

The important message is that for nuclear technology to gain and grow market share it must benefit sufficiently from learning to keep it competitive with competing energy technologies. For such learning to take place experience must be gained.

INPRO defined two Basic Principles, five User Requirements and several Criteria in the area of Economics. Table I shows the defined Basic Principles.

Table I : Basic Principles for Economics

Basic Principle 1 : *The cost of energy from innovative nuclear energy systems, taking all costs and credits into account, must be competitive with that of alternative energy sources.*
Basic Principle 2 : *Innovative Nuclear Energy Systems must represent an attractive investment compared with other major capital investments.*

Basic Principle 1 reflects the fact that, given options, customers will tend to choose the lowest cost option. All life-cycle costs included in the energy system must be accounted for. Choices of energy supply do not depend only on the up-front cost. Other factors associated with competing energy sources, such as safety, environmental impacts and socio-economic benefits, enter into the decision-making process.

As stated in Basic Principle 2, the development and deployment of INS requires investment, so investors must be convinced that INS represent a wise investment. The Internal Rate of Return (IRR) and the Net Present Value (NPV) must be attractive compared with investments in competing energy technologies. Private sector investors will be attracted by a competitive IRR, while Net Present Value analysis, which can take into account all benefits such as security of energy supply and technology development is of more interest to government investors.

IV.B. Sustainability and Environment

There exists international and strong interest and support for the concept of sustainability, which expresses that the present generation should not compromise the ability of future generations to fulfil their needs. Nuclear power supports sustainable development by providing much needed energy with relative low burden on the atmosphere, water and land use. Further deployment of nuclear power would help to alleviate the environmental burden caused by other forms of energy production, particularly the burning of fossil fuels. Two Basic Principles have been defined in this area (Table II), the first dealing with the acceptability of environmental effects caused by nuclear energy and the second dealing with the efficient use of non-renewable resources. Derived from those Basic Principles, four User Requirements and several corresponding Criteria were defined.

Table II : Basic Principles for Sustainability and Environment

Basic Principle 1 : *The expected (best estimate) adverse environmental effects of the INS must be well within the performance envelope of current nuclear energy systems delivering similar energy products.*
Basic Principle 2 : *The INS must be capable of contributing to energy needs in the future while making efficient use of non-renewable resources.*

Protection of the environment from harmful effects is seen to be fundamental to sustainability. Adherence to this principle requires that the future must be left with a healthy environment. Nevertheless the major environmental advantages of nuclear technology in meeting global energy needs, the potential adverse effects that the various components of the nuclear fuel cycle may have on the environment must be prevented or mitigated effectively to make nuclear energy sustainable in the long term. Environmental effects include : physical, chemical or biological changes in the environment; health effects on people, plants and animals; effects on quality of life of people; etc.. Both radiological and non-radiological effects as well as trade-offs and synergies among the effects form different system components and different environmental stressors need to be considered.

To be sustainable the system must not run out of important resources part way through its intended lifetime. These resources include fissile/fertile materials, water and other critical materials. The system should also use them at least as efficiently as acceptable alternatives, both nuclear and non-nuclear.

All relevant factors (sources, stressors, pathways, receptors and endpoints) must be accounted for in the analysis of the environmental effects of a proposed energy system, and the environmental performance of a proposed technology needs to be evaluated as an integrated whole by considering the likely environmental effects of the entire collection of process, activities and facilities in the energy system at all stages of its life cycle.

IV.C. Safety of Nuclear Installations

There is a worldwide consensus on the General Nuclear Safety Objective[3] : "To protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards".

Derived from this objective, the fundamental safety functions for nuclear reactors are to : control reactivity, remove heat from core, confine radioactive materials and shield radiation. For fuel cycle installations, the safety functions are to : control sub-criticality and chemistry, remove decay heat from radionuclides, confine radioactivity and shield radiation.

To ensure that INS will fulfil the fundamental safety functions, INPRO has defined five Basic Principles (Table III) and derived from them twenty seven User Requirements and several Criteria.

Table III : Basic Principles for Safety of Nuclear Installations

Basic Principle 1 : *INS installations shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and the levels of protection in defence-in-depth shall be more independent form each other than in current installations.*
Basic Principle 2 : *INS installations shall prevent, reduce or contain releases (in that order of priority) of radioactive and other hazardous material in construction, decommissioning and accidents to the point that these risks are comparable to that of industrial facilities used for similar purposes.*
Basic Principle 3 : *INS installations shall incorporate increased emphasis on inherent safety characteristics as a part of their fundamental safety approach.*
Basic Principle 4 : *INS installations shall include associated RD&D work to bring the knowledge of plant characteristics and the capability of computer codes used for safety analyses to at least the same confidence level as for the existing plants.*
Basic Principle 5 : *INS facilities shall include a holistic life-cycle analysis encompassing the effect on people and on the environment of the entire integrated fuel cycle.*

INPRO expects that INS will incorporate enhanced defence-in-depth as part of their basic approach to safety, but with more independence of the different levels of protection in the defence-in-depth strategy, and with an increased emphasis on inherent safety characteristics and passive safety features.

The general directions for innovation to enhance the levels of defence-in-depth are presented in Table IV.

Table IV. Innovative direction to enhance the levels of defence-in-depth

Level of defence-in-depth	Objectives[4]	Innovation direction (INPRO)	
1	Prevention of abnormal operations and failures.	Enhance prevention by increased emphasis on inherently safe design characteristics and passive safety features.	More independence of levels from each other
2	Control of abnormal operation and detection of failures.	Give priority to advanced control and monitoring systems with enhanced reliability, intelligence and limiting features.	
3	Control of accidents within the design basis.	Achieve fundamental safety functions by optimised combination of active and passive design features; limit fuel failures; increase grace period to several hours.	
4	Control of severe plant conditions, including prevention and mitigation of the consequence of severe accidents.	Increase reliability of systems to control complex accident sequences; decrease severe core damage frequency by at least one order of magnitude, and even more for urban-sited facilities.	
5	Mitigation of radiological consequences of significant releases of radioactive materials.	No need for evacuation or relocation measures outside the plant site.	

The end point should be the prevention, reduction and containment of radioactive releases to make the risk of INS comparable to that of industrial facilities used for similar purposes so that for INS there will be no need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility.

RD&D must be carried out before deploying INS to bring the knowledge of plant characteristics and the capability of codes used for safety analyses to the same level as for existing plants. The deployment of INS should be based on a holistic life cycle analysis that takes into account the risks and impacts of the integrated fuel cycle. Safety analyses will involve a combination of deterministic and probabilistic assessments, including best estimate plus uncertainty analysis.

IV.D. Waste Management

The already existing nine principles defined by the IAEA[5] for the management of radioactive waste have been adopted by INPRO without modification (Table V). Thus, waste management is to be carried out in such a way that human health and the environment are protected now and in the future, effects beyond national borders shall be taken into account, undue burdens passed to future generations shall be avoided, waste shall be minimized, appropriate legal frame works shall be established and inter-dependencies among steps shall be taken into account.

Table V : Basic Principles for Waste Management

Basic Principle 1 : *Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.*
Basic Principle 2 : *Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.*
Basic Principle 3 : *Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.*
Basic Principle 4 : *Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.*
Basic Principle 5 : *Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.*
Basic Principle 6 : *Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.*
Basic Principle 7 : *Generation of radioactive waste shall be kept to a minimum practicable.*
Basic Principle 8 : *Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.*
Basic Principle 9 : *The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.*

These principles in turn lead to INPRO requirements to specify a permanently safe end state for all wastes and to move wastes to its end state as early as practical, to ensure that intermediate steps do not inhibit or complicate the achievement of the end state, that the design of waste management practices and facilities be optimised as part of the optimisation of the overall energy system and life cycle, and for assets to cover the costs of managing all wastes in the life cycle to be accumulated to cover the accumulated liability at any stage of the life cycle. It is also expected that prior work carried out by the IAEA in waste management will be used to the extent possible. RD&D is recommended to be carried out in a number of areas including partitioning and transmutation and long term human factors analysis to facilitate assessments of long term risks for waste management systems that require long term institutional controls.

IV.E. Proliferation Resistance

In designing future nuclear energy systems, it is important to consider the potential for such systems being misused for the purpose of producing nuclear weapons. Such considerations are among the key considerations behind the international non-proliferation regime, a fundamental component of which is the IAEA safeguards system. INPRO set out to provide guidance on incorporating Proliferation Resistance into INS. The INPRO results in this area are largely based on the international consensus reached in October 2002 at a meeting held in Como, Italy.

Generally, two types of proliferation resistance measures or features are distinguished : intrinsic and extrinsic. Intrinsic features result from the technical design of INS including those that facilitate the implementation of extrinsic measures. Extrinsic measures are based on States' decisions and undertakings related to nuclear energy systems.

Intrinsic features consist of technical features that : a) reduce the attractiveness for nuclear weapons programmes of nuclear material during production, use, transport, storage and disposal, including material characteristics such as isotopic content, chemical form, bulk and mass, and radiation properties ; b) prevent or inhibit the diversion of nuclear material, including the confining of nuclear material to locations with limited points of access, and materials that are difficult to move without being detected because of size, weight, or radiation ; c) prevent or inhibit the undeclared production of direct-use material, including reactors designed to prevent undeclared target materials from being irradiated in or near the core of a reactor ; reactor cores with small reactivity margins that would prevent operation of the reactor with undeclared targets ; and fuel cycle facilities and processes that are difficult to modify; and d) that facilitate nuclear material accounting and verification, including continuity of knowledge.

Five categories of extrinsic features are defined, as follows : commitments, obligations and policies of states, such as the Treaty on Non-Proliferation of Nuclear Weapons and the IAEA safeguards agreements ; agreements between nuclear material exporting and importing states ; commercial, legal or institutional arrangements that control access to nuclear material and technology ; verification measures by the IAEA or by regional, bilateral and national measures ; and legal and institutional measures to address violations of measures defined above.

INPRO has produced Basic Principles (Table VI) that require : the minimization of the possibilities of misusing nuclear material in INS ; a balanced and optimised combination of intrinsic features and extrinsic measures ; the development and implementation of intrinsic features ; and a clear, documented and transparent method of assessing proliferation resistance.

Table VI : Basic Principles for Proliferation Resistance

Basic Principle 1 : *Proliferation resistant features and measures should be provided in INS to minimize the possibilities of misuse of nuclear materials for nuclear weapons.*
Basic Principle 2 : *Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself.*
Basic Principle 3 : *Extrinsic proliferation resistance measures, such as control and verification measures will remain essential, whatever the level of effectiveness of intrinsic features.*
Basic Principle 4 : *From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged.*
Basic Principle 5 : *Communication between stakeholders will be facilitated by clear, documented and transparent methodologies for comparison or evaluation/assessment of proliferation resistance.*

To comply with these Basic Principles requires the application of the concept of defence-in-depth by, e.g., incorporating redundant and complementary measures ; an early consideration of proliferation resistance in the development and design of INS ; and the utilization of intrinsic features to increase the efficiency of extrinsic measures. RD&D is needed in a number of areas, in particular, in developing a process to assess the proliferation resistance of a defined INS.

In total, INPRO defined five User Requirements and several Criteria in this area.

IV.F. Cross Cutting Issues

Issues other than technical requirements are important to potential users of INS. Many of the factors that will either facilitate or obstruct the on-going deployment of nuclear power over the next fifty years are *Cross Cutting Issues* that relate to nuclear power infrastructure, international cooperation, and human resources. Nuclear power infrastructure comprises all features / substructures that are necessary in a given country for the successful deployment of nuclear power plants including legal, institutional, industrial, economic and social features / substructures. The SRES scenarios indicate that the growth of nuclear power will be facilitated by globalization and internationalization of the world economy, and that the growth of demand in developing countries will be a major consideration. Globalization and the importance of developing countries in future world energy markets point to the need to adapt infrastructures, both nationally and regionally, and to do so in a way that will facilitate the deployment of nuclear power systems in developing countries.

In a globalizing world with a growing need for sustainable energy, harmonization of regulations and licensing procedures could facilitate the application of nuclear technology. Such harmonization among different markets is in the interest of suppliers and developers of technology as well as users and investors. The development of innovative reactors to comply with the Basic Principles, User Requirements and Criteria set out in this project should facilitate such harmonization and could make it possible to change the way the production of nuclear energy is regulated. When, for example, the risks from INS are 'comparable to that of industrial facilities used for similar purposes,' and 'there is no need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility,' the requirements for licensing could possibly be simplified. In developing countries, and amongst them countries that do not have a highly developed nuclear knowledge base and infrastructure, the development of regional or international licensing and regulatory mechanisms and organizations could play an important role. Additional factors that would be expected to favour the deployment of INS, particularly in developing countries include: optimisation of the overall nuclear energy system by considering component facilities located in different countries as part of an international multi-component system; recognizing the needs of developing countries that have a limited infrastructure and a real but limited need for nuclear energy; vendor countries offering a full-scope service, up to and including the provisions of management and operations.

The life cycle of nuclear power systems, including design, construction, operation, decommissioning, and the waste management, extends well over fifty years in most cases and can easily extend well beyond one hundred years. Thus, a firm long-term commitment of the government and other stakeholders is seen as a requirement for the successful implementation and operation of a nuclear power investment and a condition for public acceptance. Clear communications on energy demands and supply options are important to developing an understanding of the necessity for and the benefits to be obtained from such long-term commitments. A clear enunciation of the potential role of nuclear energy in addressing climate change concerns in a sustainable and economic manner, together with the performance of existing plants can play an important role in such communications.

The development and use of nuclear power technology requires adequate human resources and knowledge. Globalization brings with it the opportunity to draw on a much broader pool of resources rather than striving to maintain a complete domestic capability across the many disciplines of science and engineering that constitute the range of technologies on which nuclear energy systems depend. International cooperation in science and development can assist with optimizing the deployment of scarce manpower and, just as important, the construction and operation of large-scale research and engineering test facilities.

V. INS ASSESSMENT – INPRO METHODOLOGY

INPRO has also developed a methodology for evaluating INS, the INPRO *Methodology*. It comprises the INPRO Basic Principles, User Requirements, and Criteria, and a set of tables and guidance on their use, that can be used to evaluate a given INS, or a component of such a system on a national, regional and/or global basis.

An assessment of how well an INS complies with Basic Principles, User Requirements and Criteria, is a bottom-up process, which starts with the Judgement of the ability to comply with each criterion. The set of defined Judgement values is presented in Table VII.

Table VII. Outcomes of an INS assessment against a defined criterion

Judgment	*Meaning of the Judgment*
Very High Potential to satisfy the Criterion (VHP).	All components (parameters) of the Approach of the INS being assessed have been theoretically demonstrated and, where necessary, experimentally verified and meet the Criterion.
High Potential to satisfy the Criterion (HP).	Not all components (parameters) of the Approach of the INS being assessed have been theoretically demonstrated or experimentally verified, but there is theoretical evidence that this Approach could meet the Criterion.
Potential to satisfy the Criterion (P).	No theoretical or experimental evidence that the Criterion cannot be met, due to some physical, technological or other limitation which cannot be overcome by later technology developments.
No Potential to satisfy the Criterion (NP).	Theoretical or experimental evidence that the Criterion cannot be met by means of technology development due to some physical, technological or other limitation. Explanation should be provided.

An INS is judged to have a Very High Potential to satisfy a given User Requirement when it has Very High Potential to meet all the Criteria linked to this User Requirement. If the Judgement for at least one of the associated Criterion is only High Potential, then the Judgement for this User Requirement is High Potential. A similar logic is applied to determine the Judgement of a Basic Principle, based on the Judgement of the User Requirements associated with it.

Additional factors also enter into the assessment, including the maturity status of the INS. As a step in the INPRO methodology, each technology should be classified into the appropriate category defined below :

Category 1 (Proven): Well demonstrated technologies, successfully used in nuclear energy systems (and/or in other industries), for which there is an established industrial infrastructure, an experimental and technological base, and a reliable set of physical and mathematical models.

Category 2 (Developed): Technologies that have not yet been successfully demonstrated in an actual nuclear energy system, but that are at an advanced stage of development based on extensive analytical and experimental work, and that have been demonstrated in either pilot plant or in large-scale engineering facilities simulating all relevant features of an actual nuclear energy system. The industrial infrastructure to realize the technology on a large scale is considered feasible, though it may not yet exist.

Category 3 (Evolving): Technologies under development, for which demonstration and pilot industrial facilities have been set up, and there is an experimental base and major engineering processes are under way, physical and mathematical models have been developed to a significant extent and are continually improving, but for which there is still no industrial infrastructure.

Category 4 (Conceptual): Technologies proposed for development, for which only individual features and prospects for application have been enunciated so far. In the initial development stages of such technologies it may be possible to "borrow" the experimental databases and mathematical models from other technology options, but it is recognized that, eventually, additional experimental facilities and new mathematical models will be necessary. Time and resources will be needed to establish such facilities and models and to demonstrate the technology.

This information will be useful in assessing the uncertainty to be assigned to the assessment, and in estimating the level of effort required to develop an innovative or evolutionary technology from its current level of development to commercial application.

Additional effort is needed to validate and adjust this methodology. For this purpose, Case Studies are being performed by some INPRO Member States and different teams of international experts.

VI. ONGOING ACTIVITIES

After the completion of Phase 1A, Phase 1B was started in June 2003. In the first part of this phase, case studies are being performed to validate and adjust the INPRO methodology by applying it to the assessment of specific INS. These case studies are evaluating the following :

- Whether the INPRO Basic Principles, User Requirements and Criteria are understandable, workable, consistent, comprehensive and dependent or independent of the system studied.
- Whether the INPRO methodology is useful for providing an overall assessment of the system, for comparing different systems, components and approaches, identifying regional specificities, and for identifying the directions and objectives of RD&D needed for the further development of a given INS.

Four 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.

In addition, several case studies are being performed by individual international experts, covering those technologies not addressed by the National Case Studies, in order to obtain a validation of the Methodology as complete as possible.

After considering the final results of both national and individual case studies, the definitive INPRO Methodology, updated and validated, will be available for realizing the second part of Phase 1B, which is the assessment of selected INS made available by Member States. This assessment will be performed by Member States.

Also during this phase, the Phase 1A Report is being presented to various interest groups, amongst them, nuclear industry representatives and national regulatory authorities. These groups will be involved in the early stages of innovative developments.

VII. OUTLOOK

Upon successful completion of Phase 1B, taking into account advice form the Steering Committee of INPRO, and with the approval of participating Member States, a second phase of INPRO may be initiated. Drawing on the results from the first phase, it will be directed to :

- Examining in the context of available technologies the feasibility of commencing an international project.
- Identifying technologies, which might be appropriate for implementation by Member States of such an international project.

VIII. CONCLUSIONS

The final results of INPRO Phase 1A were presented in a IAEA document published in June 2003. Phase 1A was an important first step toward INPRO's two objectives of (1) ensuring the availability of nuclear energy to contribute to meeting growing global energy needs in the 21st century and (2) bringing together prospective buyers and sellers of nuclear technology, and developing and developed countries, to jointly consider actions needed to accelerate nuclear innovation in directions most likely to be useful to the energy markets of the future.

The 21st century promises the most competitive, globalized markets in human history, the most rapid pace of technological change ever, and the greatest expansion of energy use, particularly in developing countries. For a technology to make a truly substantial contribution to energy supplies, innovation is essential. It will be the defining feature of a successful nuclear industry and a critical feature of international co-operation in support of that industry, cooperation that ranges from joint scientific and technological initiatives, to safety standards and guidelines, and to security and safeguards activities. Innovation is also essential to attract a growing, high-quality pool of talented scientists, engineers and technicians needed to support a truly substantial nuclear contribution to global energy supplies.

To help co-ordinate and guide the development of INS, INPRO Phase 1A has set out initial Basic Principles, User Requirements and corresponding Criteria in the areas of Economics, Environment, Safety, Waste management, and Proliferation resistance. Cross-cutting issues related to infrastructure and international co-operation have also been discussed. A methodology for assessing INS has been created for the use of Member States and independent analysts. It complements and builds upon requirements and criteria set out in existing documents such as the IAEA Safety Standards Series. This output of INPRO, the Phase 1A Report, is expected to be validated and sharpened during the current Phase 1B, based on the feedback from the case studies being performed.

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NOMENCLATURE

ADS :	Accelerator Driven System
DUPIC :	Direct Use of spent PWR fuel in CANDU reactors
FBR :	Fast Breeder Reactor
INS :	Innovative Nuclear Energy System
RD&D	Research, development and demonstration

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