INTERNATIONAL PROJECT ON INNOVATIVE NUCLEAR REACTORS AND FUEL CYCLES (INPRO)

The Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is based on an Agency General Conference resolution in September 2000 inviting all interested Member States, both technology suppliers and technology users, to consider jointly international and national actions to achieve desired innovations in nuclear reactors and fuel cycles. In subsequent resolutions at the 2001 and 2002 sessions of the General Conference, Member States reinforced their strong support for the project. Additional endorsement came in the UN General Assembly resolutions on the IAEA (A/RES/56/94 in December 2001 and A/RES/57/9 in November 2002) that emphasize "the unique role that the Agency can play in developing user requirements and in addressing safeguards, safety and environmental questions for innovative reactors and their fuel cycles" and stress "the need for international collaboration in the development of innovative nuclear technology".

INPRO is an Agency-wide project involving all relevant Departments. As of April 2003, it has 15 members (Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Pakistan, Russian Federation, Republic of Korea, Spain, Switzerland, Netherlands, Turkey and the European Commission). More than twenty cost-free experts have been nominated by participating countries.

INPRO's Terms of Reference were established at a meeting of senior officials from 25 Member States and international organizations in November 2000. A Steering Committee, composed of members (participants from countries providing extrabudgetary resources) and observers from interested Member States and international organizations, was established to provide overall guidance, advise on planning and methods of work and review results. The Steering Committee first met in May 2001 to review and approve the project's organizational structure, the outline of the proposed first-phase report, resources, the overall schedule, the workplan and task contents. The second and third meetings of the Steering Committee, in December 2001 and May 2002, reviewed initial progress reports and approved the continued development of the project. They included observers from 12 countries — Australia, Belarus, Belgium, Chile, Croatia, the Czech Republic, France, Italy, Japan, South Africa, United Kingdom and the United States of America — and from four international organizations: the International Institute for Applied Systems Analysis, the International Science and Technology Center, the International Energy Agency and the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency. The meetings also focused on mechanisms and criteria to strengthen direct scientific input into the project from both member and observer countries and organizations and on preparations for the Phase-IA report. The fourth meeting of the Steering Committee, in December 2002, reviewed a first draft of the Phase-IA report, and the fifth meeting, in May 2003, reviewed the final draft prior to its release the following month.

The project's overall objectives are to ensure that nuclear energy is available to help meet the energy needs of the twenty-first century and contribute to sustainable development; to engage both technology holders and technology users; and to promote innovations in nuclear reactors and fuel cycles to meet expected future requirements in terms of economics, safety, waste management, environmental impacts, proliferation resistance and public acceptance. Phase-IA focused on defining such "user requirements", which can be used by the project or others to help design R&D strategies aimed to meet anticipated needs by the middle of the century. INPRO has developed user requirements in five areas: economics, environmental impacts, safety, waste management and proliferation resistance. Phase-IA also addressed "cross-cutting issues", which include infrastructure requirements, industrial requirements, legal and institutional requirements, as well as education, training and R&D implications and socio-political implications. A seventh task is developing assessment methods and criteria for applying these user requirements to specific innovative nuclear designs. In Phase-IB, Member States will examine innovative designs against Phase-IA's criteria and requirements.

Phase-IA Report

Progress to date is described in the Phase-IA report, released prior to the June 2003 conference in Vienna on Innovative Technologies for Nuclear Fuel Cycles and Nuclear Power. The remainder of this document summarizes the Phase-I A report.

Energy Demand and Economics

INPRO's analysis of future energy demand and economic requirements starts with scenarios. The objective is innovation to develop products people will want in the middle of the century, and scenarios are the vehicle for systematically describing what they might want. Since there is uncertainty about what people will want, one scenario is not enough. Several are needed to reflect the range of current uncertainty. The principal outputs of the INPRO scenarios are projected demands in terms of which nuclear products are demanded (electricity, hydrogen, nuclear heat, desalination), how much of each, where, and when.

INPRO's starting point is the 40 non-greenhouse-gas-mitigation scenarios in the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC)[1]. Given their international authorship and comprehensive review by governments and scientific experts, the SRES scenarios are the state of the art in long-term energy scenarios. As recommended in the SRES, INPRO selects one scenario from each of the four SRES "scenario families."

- The A1 storyline and scenario family describe a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.
- The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describe a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures

[1] IPCC (Intergovernmental Panel on Climate Change), 2000: *Special Report on Emission Scenarios*. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, (http://www.grida.no/climate/ipcc/emission/index.htm).

toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental challenges, including improved equity, but without additional climate initiatives.

- The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental challenges. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the storyline is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

For each of the A2, B1, and B2 storylines, INPRO analyses a single scenario representative of central tendencies within the scenario family. For the A1 storyline, SRES projections showed that greenhouse gas emissions (the principal focus of SRES) vary greatly depending on the technologies assumed to progress most quickly. The A1 variation used by INPRO is the A1T Scenario, which assumes that advances in non-fossil technologies — renewables, nuclear and high-efficiency conservation technologies — make them most cost-competitive. Although the A1T Scenario in the SRES — like all the SRES scenarios — describes a plausible outcome in a world that *explicitly eschews policies limiting greenhouse gas (GHG) emissions,* while aggressively pursuing high efficiency and non-fossil technologies, from the perspective of INPRO it also describes a plausible outcome in a world that is just like the SRES A1T world with one exception — it *does* choose to implement explicit policies on GHG emissions. The A1T emission trajectory for GHGs is consistent with stabilizing the atmospheric carbon concentration at about 560 parts per million by volume (ppmv), a level potentially consistent with the objectives of the UN Framework Convention on Climate Change (UNFCCC). It is also a plausible trajectory for an A1T-like world that includes the Kyoto Protocol and successive (or alternative) more stringent agreements. Thus the A1T Scenario can be considered a plausible outcome in a high-growth, high-tech globalized world either with or without explicit GHG constraints.

The B1 Scenario's GHG emissions are also consistent with the objectives of the UNFCCC, and it can similarly be viewed as a plausible outcome for a B1-like world either with or without explicit GHG constraints. Thus two of the four INPRO scenarios (A1T and B1) are consistent with future GHG limitations reflecting UNFCCC objectives, while the A2 and B2 Scenarios project higher GHG emissions currently considered inconsistent with the UNFCCC.

Six modelling teams quantified the SRES scenarios using different models. Two modelling teams were from Japan, two from Europe, and two from the USA. INPRO uses quantifications from the MESSAGE model of the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

For each of the four selected SRES scenarios, the INPRO Phase-IA report summarizes highlights of its prospective mid-century market for nuclear energy. Global nuclear capacity grows fastest in the A1T Scenario, but peaks around 2070–2080 at 175 exajoules (EJ) and then declines. Nuclear expansion in the B1 Scenario follows the same pattern as in the A1T Scenario, but at a much lower level, peaking at only 47 EJ in 2070–2080. The expansion patterns projected in the A2 and B2 Scenarios are essentially identical, growing steadily throughout the century to about 140 EJ in 2100. Highlights of the prospective mid-century nuclear markets for the four scenarios are as follows.

For A1T:

- The principal product market is electricity with a significant market also in hydrogen, especially after 2030.
- Until 2030, electricity capacity additions are greatest in Asia, with ROW[2] and OECD tied for second. After 2030, principal growth is shared equally between ROW and Asia.
- Hydrogen capacity growth is initially dominated by the OECD. It shifts to Asia and ROW around 2050.
- Initial competition for new electricity capacity is initially quite balanced between coal, gas, nuclear, and solar. Coal drops out around 2020 and gas around 2040, leaving the competition to nuclear and solar.
- In REF[2] and OECD, however, nuclear is assumed to lose out after 2050–60 to solar and, in REF, to hydro and wind. The market for new nuclear power plants (NPPs) shifts strongly to Asia.

For A2:

- The product market is exclusively electricity. There is no hydrogen production from NPPs.
- Capacity additions are principally in the OECD before 2030, followed by Asia and ROW. After 2030 these three regions continue to dominate capacity additions more or less equally. Capacity additions are mainly in countries that lack competing fuel resources.
- Until 2030, competition for new capacity additions is largely from coal and to a lesser extent gas. After 2030 solar is nuclear's principal competitor.
- In the OECD and REF, however, coal is the dominant competitor as late as 2050–60.
- Nuclear is assumed to fare a bit better than solar in the OECD, while solar is assumed to fare much better in Asia after 2030.

For B1:

- B1 is distinctive in that global and regional energy use (primary, final and electricity) peak around 2060–2080 and then decline.
- Much is similar to the A1T Scenario, but the shift from the OECD to developing region markets is much faster.
- Principal product markets are electricity and, especially after 2030, hydrogen.
- For both electricity and hydrogen capacity, additions are greatest in ROW, then Asia, then OECD, and, well behind, REF.
- After 2030, the prime principal markets for new capacity are largely ROW and Asia.
- Nuclear's principal competition for new electricity capacity is solar and (until 2040) gas.

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[2] SRES divides the world into four regions. The OECD region includes all countries belonging to the OECD as of 1990 and corresponds to the Annex II countries in the UNFCCC. The REF region comprises countries undergoing economic reform and groups together the East European countries and the Newly Independent States of the former Soviet Union. It includes Annex I countries outside Annex II as defined in the UNFCCC. The Asia region stands for all developing (non-Annex I) countries in Asia. The ALM region, which is re-labelled the "ROW region" in INPRO, stands for the rest of the world and includes all developing (non-Annex I) countries in Africa, Latin America, and the Middle East.

- Nuclear's principal competition for new hydrogen capacity is gas, biomass, and (after 2040) solar.
- The B1 modellers assume solar largely beats out nuclear for both electricity and hydrogen generation.

For B2:

- Electricity remains the primary product of NPPs.
- The principal competition is natural gas until about 2030, then solar power.
- Nuclear expansion is greatest in Asia and OECD until 2030. Around 2040–50 increases are greatest in Asia and ROW, effectively shifting the nuclear energy markets to the leading emerging economies.
- In developed countries, the preferred strategy may be to focus on capturing economies of scale with large plants (modular or monolithic) that need a minimum of new sites.
- In the regionalized B2 world, large developing countries with nuclear experience are better able to build up the required domestic infrastructure for nuclear expansion.
- Smaller developing countries, currently without nuclear power, will find it difficult to start nuclear programmes, but may be suitable markets for small "black box" reactors.

For INPRO it is important that the SRES results are not viewed as tight constraints, but as indications of opportunities. An important question is what additional market potential there might be for nuclear energy if the nuclear industry were to improve nuclear costs more quickly, relative to its competitors, than is assumed in the SRES calculations. The Phase-IA report therefore creates an "aggressive-nuclear-improvement" variation for each of the four SRES scenarios by assuming reasonable nuclear incursions in the expensive ends of the market shares of key competitors.

The basic economic requirements for nuclear energy are that it be cost effective and an attractive investment compared with alternatives. These are moving targets, because technology, experience and the competition are constantly improving. INPRO therefore focuses on rates of improvement rather than unmoving cost targets at specific dates. Learning rates are used to measure improvement, where the learning rate is defined as the percentage reduction in specific cost (e.g. $/kW(e)) for each doubling of cumulative installed capacity (e.g. GW(e)).

The procedure is to: estimate implied learning rates for the SRES scenarios; build a variation of the MESSAGE model incorporating learning rates, so that costs decrease with experience rather than with time as in the original SRES runs; through sensitivity studies find learning rates consistent with INPRO's aggressive-nuclear-improvement variations on the SRES scenarios; and compare these to empirical technology learning rates and the implied SRES learning rates to suggest learning rate targets consistent with different scenarios.

Implied nuclear learning rates in the four selected SRES scenarios range from 0%–5%. The learning rates required to reach the build-up trajectories in the aggressive-nuclear-improvement variations are 6%–10%. The future capital and generation costs for nuclear energy implied by each scenario are calculated as potential starting points for setting future cost targets. Future refinements will likely recommend targets below values derived directly from the scenarios, depending on prospective investors (whether government or private) and their respective planning horizons.

Sustainability and Environment

In the field of sustainability and the environment, the Phase-IA report starts with two basic principles.

The first basic principle addresses the acceptability of environmental effects and states that expected adverse environmental effects of a new nuclear energy system must be well within the performance envelope of current nuclear systems delivering similar products. The second principle, labelled "fitness for purpose", states that the new system must be capable of contributing to energy needs in the 21st century while making efficient use of non-renewable resources.

Each basic principle then gives rise to several user requirements, and each user requirement gives rise to one or more criteria. Each criterion specifies an indicator and an acceptance limit. The indicator may be based on a single parameter, an aggregate variable, or a status statement. The acceptance limit, which can be either qualitative or quantitative, is the dividing line between acceptable and unacceptable values for the indicator.

There are two user requirements associated with the basic principle on the acceptability of environmental effects. The first is that environmental stressors (see Figure 1) from all parts of a new nuclear system should be controllable, over the full system life cycle, to levels at or superior to current standards. The associated indicators are simply the levels of all relevant stressors, and the acceptance limits are current standards. The second user requirement is that adverse environmental impacts should be as low as reasonably practicable (ALARP). The indicators are the levels of adverse environmental impacts, and the acceptance limits are defined by ALARP.

For the "fitness for purpose" basic principle, the Phase-IA report offers two user requirements. The first effectively requires that a new nuclear system be able to meet "a significant fraction of the world's energy needs in the 21st century" without running into fuel or other material constraints. The second states that, "within an acceptably short period" the system's energy output must exceed its energy input requirement. For both user requirements the Phase-IA report lists criteria that, while quantitative in concept, do not specify at this stage specific numerical acceptance limits.

Life cycle assessment (LCA) and material flow analysis (MFA) are the recommended methods for assuring a comprehensive evaluation of a system's environmental performance, including all sources, stressors, pathways, receptors and end points (see Figure 1). For nuclear technologies, the following are particularly important.

- Fertile and fissile materials (e.g. ^{235}U, ^{239}Pu) as well as other strategic materials. The net flow of these materials should be evaluated against proven reserves, inventories and production rates. The analysis must take into account the time-dependence of the material flows. In particular, the use of materials during an initial transient in establishing an equilibrium fuel cycle must be accounted for. Recycling of these materials should be credited in the assessment.

- Materials that pose a particular radioactive risk (e.g. radioactive/toxic). Included here are flows of materials in the high level waste stream, including minor actinides and fission products. Important factors are the total amounts of the materials, their accessibility to the environment, the time over which they remain in proximity to the environment and their mobility in environmental pathways.

- Chemicals of particular environmental significance. Their environmental effects should be assessed in parallel with those of radioactive materials.
- Discharges of radioactive and chemically hazardous materials and heat from normal and abnormal operation.
- The use and depletion of natural resources (e.g. water and land) and of energy by all parts of the system.

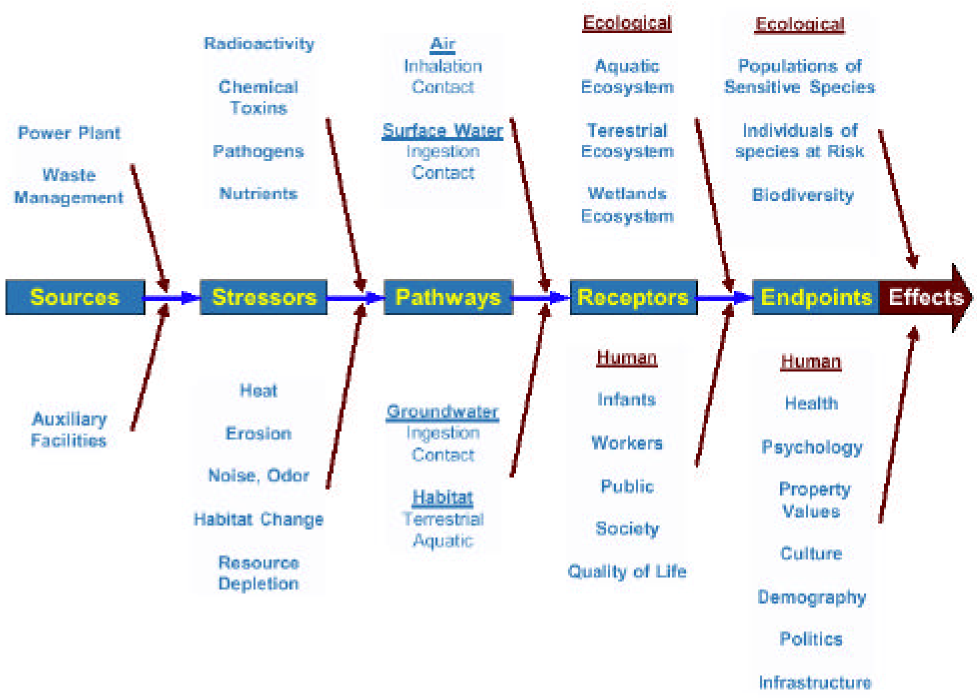

Fig. 1. Factors in environmental assessment.

Safety

There is a worldwide consensus on one general nuclear safety objective: to protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards. For normal operation of all nuclear facilities this means that exposures to radiation must be kept below prescribed limits and as low as reasonably achievable (ALARA), taking all economic and social factors into account. For possible accidents, it means that all practical measures are taken to prevent accidents and to mitigate their consequences, should they occur. This includes ensuring that the radiological consequences of all accidents accounted for in the facility's design would be minor or below prescribed limits, and ensuring that the likelihood of worse accidents is extremely low.

Figure 2 shows INPRO's approach for translating this consensus nuclear safety objective into more specific user requirements and criteria. It recognizes the fundamental safety functions for nuclear reactors (control reactivity, remove heat from the core, and confine radioactive materials and shield radiation) and for fuel cycle installations including spent fuel storage at reactor sites (control sub-criticality and chemistry, remove decay heat from radionuclides, and confine radioactivity and shield radiation).

"Defence in depth" is the appropriate overall strategy. It is a twofold strategy, first, to prevent accidents and, second, if prevention fails, to limit their consequences. Figure 2 shows five defence in depth levels. For innovative designs, INPRO highlights the importance of increasing the independence of defence in depth mechanisms across different levels so that a failure at one level does not propagate to subsequent levels. Possible approaches include more extensive use of inherent safety characteristics and greater separation of redundant systems.

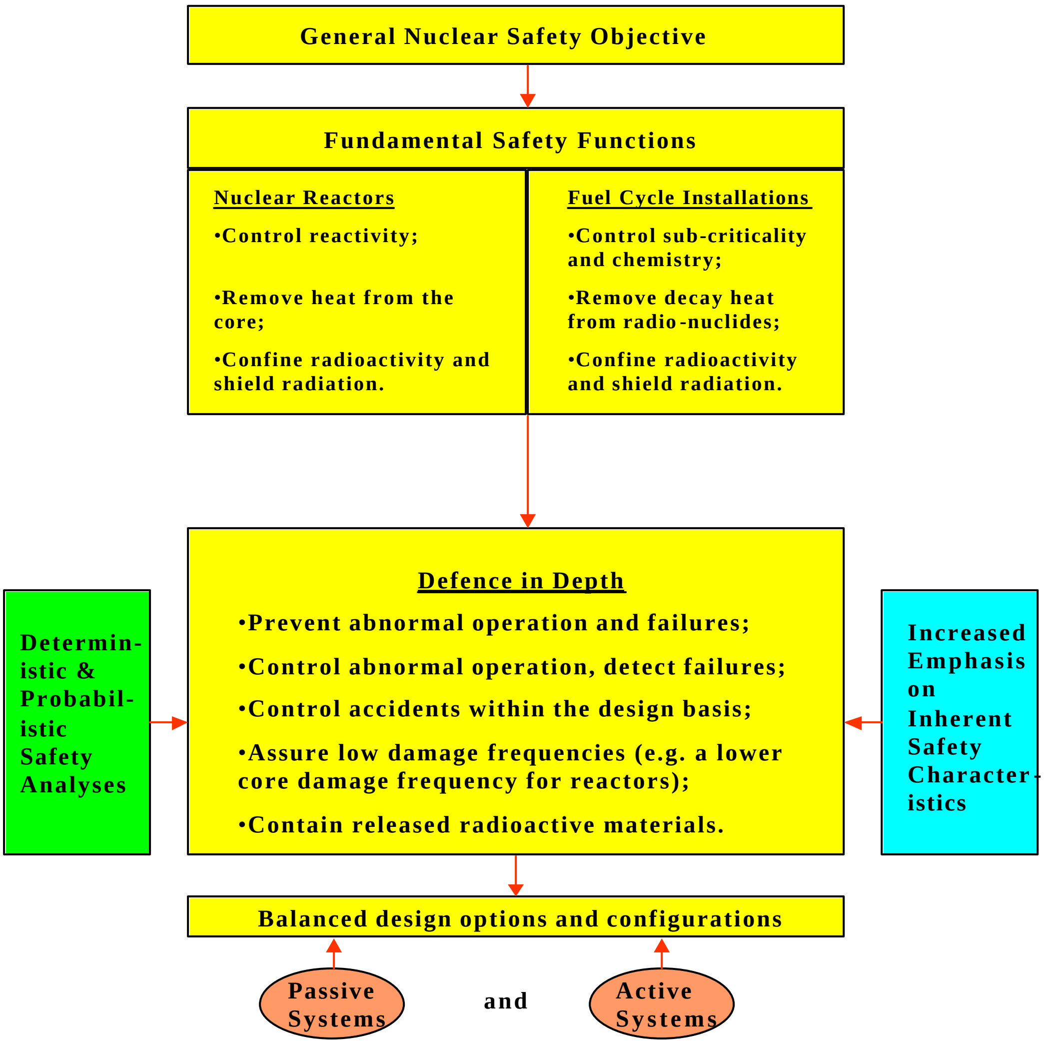

Figure 2. Development of safety-related user requirements in INPRO.

Based on this approach, INPRO derives five basic principles for safety — specifically that innovative nuclear reactors and fuel cycle installations shall:

- Incorporate enhanced defence in depth and assure that protection levels in defence in depth are more independent of each other than in current installations;
- Prevent, reduce or contain releases (in that order of priority) of radioactive and other hazardous material in construction, normal operation, decommissioning and accidents to the point that these risks are comparable to those of industrial facilities used for similar purposes;
- Give increased emphasis to inherent safety characteristics and passive safety features;
- Include associated research, development and demonstration (RD&D) to assure equal or better confidence, compared to existing plants, in the knowledge of innovative plant characteristics and the capability of computer codes for safety analyses;
- Include a holistic life-cycle analysis encompassing the effects on people and the environment of the entire integrated fuel cycle.

These five basic principles spawn a total of 27 safety-related user requirements and 46 criteria. The user requirements represent an idealization of what is desirable in safety in the future taking into account both current national and regional trends and what is likely to be technologically achievable. The associated criteria range across accident probabilities, dose limits, compliance with existing or future standards, ALARP and judgements of whether safety analyses are state-of-the art. Nearly all are, at this stage, qualitative rather than quantitative.

INPRO's chapter on safety also identifies a number of RD&D safety-related areas important to the development of innovative nuclear systems. These include better understandings of

- natural circulation phenomena, such as initiation and stability, in liquid metals and gas coolants, for two phase flow and supercritical fluid flow;
- neutronic-thermalhydraulic interaction, mainly for supercritical water and fluid states like sub cooled two phase fluid with the potential for coupled neutronic and thermal hydraulic oscillations;
- fuel performance, including dimensional and mechanical stability, possible chemical interactions between fuel elements and coolant, and mechanical-chemical interaction between fuel material and fuel element cladding;
- areas related to the transmutation of minor actinides and long-lived fission products in an accelerator driven system (ADS), ranging from proton/neutron physics (database) to the thermalhydraulics of a liquid metal cooled system;
- the use of inert fuel matrices for actinide burning in thermal reactors;
- areas related to reprocessing ranging from process control to solvent chemistry and dry processing (oxidation/reduction reactions);
- possible improvements in digital instrumentation and control (I&C); and
- possible improvements in probabilistic safety analysis (PSA) methods.

The overall emphasis for the future is on a possible new approach to implementing defence in depth that would integrate it more fully with PSA insights. To date, defence in depth has been achieved primarily through deterministic analyses based on prevention and mitigation. Risk informed decision making is expected to play an important role in the development of future reactors and fuel cycle facilities and to increase safety levels while reducing costs, in particular through the simplification of safety systems. The challenges for the future are to develop more confidence in PSA tools, to achieve an appropriate integration of deterministic and probabilistic analyses, and to demonstrate that sufficient defence in depth can be achieved through simpler and cheaper technological solutions.

Waste Management

For basic principles in the area of waste management, INPRO adopts the nine principles issued by the Agency in its Safety Fundamentals documents, *Principles of Radioactive Waste Management* (Safety Series No. 111-F).

- Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.
- Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.
- 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.
- 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.
- Radioactive waste shall be managed in a way that will not impose undue burdens on future generations.
- Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.
- Generation of radioactive waste shall be kept to the minimum practicable.
- Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.
- The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

From these, INPRO defines six user requirements and ultimately 19 associated criteria, all of which are, at this stage, relatively qualitative. The six user requirements are the following.

- Intermediate steps between the generation of waste and its end state should be taken as early as reasonably practicable. These should address all critical issues such as heat removal, criticality control, and the confinement of radioactive material. These processes should not inhibit or complicate the achievement of the end state.

- For each waste in the energy system, a permanently safe end state should be defined. The planned energy system should be such that the waste is brought to this end state as soon as reasonably practicable. The end state should be such that, on the basis of credible conservative analysis or demonstrated operation, any release of hazardous materials to the environment will be below that which is acceptable today.
- Waste management systems should be designed to ensure that their associated adverse radiological and non-radiological effects on humans are below the levels acceptable today. Since waste management systems are integral parts of the overall energy system, their designs should be optimized with respect to adverse effects as part of the optimization of the overall energy system.
- Waste management strategies should be such that adverse environmental effects from all parts of the energy system and the complete life cycle of facilities are optimized. The cumulative effects over time and space, without regard to national boundaries, should be considered.
- The energy system should be designed to minimize the generation of particularly wastes containing long-lived components that would be mobile in a repository environment.
- The costs of managing all wastes in the life cycle should be included in the estimated cost of energy from the energy system, in such a way as to cover the accumulated liability at any stage of the life cycle.

Finally, the report defines a number of broad RD&D needs in the areas of waste characterization, waste treatment, reprocessing, interim storage, partitioning and transmutation, geologic disposal and human factors analysis.

Proliferation Resistance

INPRO defines five basic principles for proliferation resistance and five user requirements after clarifying the following four key terms.

“Proliferation resistance” is the extent to which a nuclear energy system’s design and operation impedes the diversion or undeclared production of nuclear material, or misuse of technology, by states intent on acquiring nuclear weapons or other nuclear explosive devices. Thus in the INPRO Phase-IA report proliferation resistance addresses only proliferation by states. It does not include protection against the theft of fissile materials by sub-national groups or the sabotage of nuclear installations or transport systems. “Intrinsic features” are proliferation resistance features resulting from the technical design of nuclear energy systems. “Extrinsic measures” are proliferation resistance measures resulting from states’ decisions and undertakings related to nuclear energy systems. **“**Safeguards” constitute an extrinsic measure comprising legal agreements between the party having authority over the nuclear energy system and a verification or control authority, binding obligations on both parties and verification using, inter alia, on site inspections.

The five basic proliferation resistance principles are:

- Proliferation resistant features and measures should be provided in innovative nuclear energy systems to minimize the possibilities of misuse of nuclear materials for nuclear weapons.

- Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself.
- Extrinsic proliferation resistance measures, such as control and verification measures will remain essential, whatever the level of effectiveness of intrinsic features.
- From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged.
- Communication between stakeholders will be facilitated by clear, documented and transparent methods for comparison or evaluation/assessment of proliferation resistance.

The Phase-IA report then presents five user requirements with the caveat that the list of five "is not intended to be complete or exhaustive, but to provide high-level guidance".

- Proliferation resistance features and measures should be implemented in the design, construction and operation of future nuclear energy systems to help ensure that future nuclear energy systems will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.
- Future nuclear energy systems should incorporate complementary and redundant proliferation resistance features and measures that provide defence in depth.
- The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized to provide cost-effective proliferation resistance.
- Proliferation resistance should be taken into account as early as possible in the design and development of a nuclear energy system.
- Effective intrinsic proliferation resistance features should be utilized to facilitate the efficient application of extrinsic measures.

For the first of these, on the implementation of proliferation features and measures, the report presents criteria at three different levels. At the first, most aggregate level, the criterion is simply that there is confidence that proliferation resistance features and measures have been sufficiently implemented. The acceptance limit is currently qualitative, i.e. scoring an "acceptable rating" on a qualitative scale from unacceptable to outstanding. But the report also presents second and third level criteria that lay out a range of issues, intrinsic features and extrinsic measures that should be considered — from export control policies to the isotopic content of fuel. The report emphasizes that the second and third level criteria cannot be applied independently of each other. The effectiveness of some features and measures is dependent on how others are applied, and there are a number of redundancies and complementarities, all of which need to be taken into account in determining whether the top level criterion is met — i.e. that proliferation resistance features and measures have been, in aggregate, sufficiently implemented.

Associated with the second user requirement, on redundancy and defence in depth, is also a single top level criterion, requiring an "acceptable" rating on a qualitative scale that measures the effectiveness of redundant and complementary features and measures. Second level criteria are then listed reflecting how defence in depth can be strengthened by various combinations of complementary intrinsic features and extrinsic measures.

- For the third user requirement, on cost effectiveness, there is a single criterion based on cost minimization. The fourth user requirement requires that designs take proliferation resistance into account as early as possible. The report lays out several associated criteria based on different design stages at which conformance with this requirement could be checked. The fifth user requirement is designed to encourage the effective use of intrinsic features to facilitate the application of extrinsic measures. Three qualitative criteria are included addressing how much designers are aware of extrinsic measures, the extent to which intrinsic features are used in the verification approach, and the extent of agreements with the IAEA and other verification agencies on the verification approach.

Cross-cutting Issues

INPRO identifies three major cross-cutting issues — legal and institutional infrastructure, economic and industrial infrastructure, and socio-political infrastructure. The Phase-IA report emphasizes developments in all three areas that could facilitate the deployment of innovative nuclear concepts in the light of expected changes in world circumstances.

With respect to the legal and institutional infrastructure, these are:

- International co-operation in establishing more generally applicable licensing mechanisms and regulations, extending perhaps to the development of a harmonized international licensing process such that licences, national or international, are accepted by all potential user countries;
- The establishment of international or regional arrangements and institutions to diminish the burden on individual countries of developing nationally all the institutions for nuclear oversight and control; and
- Insurance of nuclear risks in the same way that other industrial risks are insured.
- With respect to the economic and industrial infrastructure, they are:
- That component facilities of the overall nuclear energy system, even if located in different countries, have to be perceived, and optimized, as part of an international multi-component system, including the final storage of waste;
- That companies or governments can facilitate the deployment of innovative nuclear energy systems by providing full-scope service, up to and including the provision of management and operation services; and
- That recognition of the specific needs of different markets, particularly in developing countries that have limited infrastructures, will facilitate nuclear expansion and better position nuclear energy systems to contribute to the security of supply in developing countries.

With respect to the socio-political infrastructure, INPRO emphasizes developments that address both public acceptance and requirements concerning human resources and knowledge, specifically:

- Innovative nuclear concepts should address concerns about safety, waste and proliferation related to public acceptance;

- Responses to such concerns should apply the highest standards of safety. Ways need to be found to facilitate the application of such standards by making available the necessary technology and knowledge to developing countries that currently lack the means to develop such standards themselves;
- Governments and other stakeholders must make a firm long term commitment to nuclear power;
- Clear communication is essential between the public and other stakeholders on future energy needs and supply options, on the potential role of nuclear energy in addressing climate change and on the performance of nuclear power facilities;
- Plans must be developed for retaining existing nuclear knowledge and experience;
- Science and development activities should be shared; and
- Multinational structures for education and development should be strengthened.

Assessment Method

The criteria developed by INPRO in each of the areas above range from simple yes-no indicators (e.g. availability of tight containment), to quantitative indicators (e.g. core damage probability), or indicators that can take several qualitative values (describing, for example, different insurance arrangements from total governmental coverage to fully privatized insurance).

Recognizing the uncertainty inherent in setting criteria now for forward looking nuclear concepts, the next step of assessing how a concept measures up against the criteria uses a graduated scale. The scale allows a concept to be judged as having a very high potential to meet a given criterion (VHP), a high potential to meet the criterion (HP), simply the potential to meet the criterion (P), or no potential (NP). INPRO's principle for aggregating across all criteria is essentially that a new concept is only as strong as its weakest link, i.e. that the aggregate rating across all criteria equals the lowest of the ratings received on the individual criteria.

The assessment method currently recognizes that different features of different nuclear systems will be at different stages of development. Judgments about their potentials to meet INPRO's criteria will thus have differing degrees of uncertainty. INPRO defines four development stages — conceptual, evolving, developed and proven — and the assessment method keeps track of the development stages of various technologies and components. This is important for estimating the time and effort required to bring a given concept to market, but the Phase-IA report stresses that, given INPRO's objective of encouraging productive innovation, less developed concepts should not be penalized simply for their lack of development relative to more proven systems.

Conclusions and Recommendations

The final section of the Phase-IA report re-emphasizes the importance of innovation and lays out four recommendations to guide INPRO's work in Phase-IB. It notes that near-term projections by the IAEA, OECD-IEA and US DOE Energy Information Administration show a declining nuclear role in coming decades. This contrasts with the IPCC Special Report on

Emissions Scenarios (SRES), where nuclear energy plays a significant role in nearly all 40 scenarios. And in some of the "aggressive nuclear improvement" scenarios developed for INPRO, nuclear energy makes a truly substantial future contribution — one that takes its percentage of the world's primary energy supply well beyond today's single digits to 30% and above. For such an expansion, innovation is essential.

Phase-IA's basic principles, user requirements, criteria and assessment method can be used by Member States and independent analysts to evaluate new concepts and guide research and development. They complement and build upon requirements and criteria set out in existing documents such as the IAEA Safety Standards Series, and they are expected to be steadily sharpened and adjusted based on feedback from early applications and case studies.

Four specific recommendations are offered for the future, specifically that:

- INPRO be continued, and that co-operation and co-ordination between INPRO and other initiatives on innovative nuclear energy systems be strengthened.
- As part of Phase-IB of INPRO, Member States define in further detail the RD&D initiatives identified in the report and set priorities. The IAEA could provide valuable assistance in facilitating co-operation among Member States and establishing complementary co-ordinated research projects (CRPs).
- Case studies be encouraged to enable Member States and independent analysts to assess prospective innovative nuclear energy systems using the INPRO methodology.
- Feedback and experience from case studies and other applications be used to sharpen and adjust the INPRO basic principles, user requirements, criteria and assessment method to continually improve their usefulness.