IAEA-TECDOC-1362

Guidance for the evaluation of innovative nuclear reactors and fuel cycles

Report of Phase 1A of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

INTERNATIONAL ATOMIC ENERGY AGENCY

June 2003

The originating Department of this publication in the IAEA was:

Department of Nuclear Energy
with contributions of the
Department of Nuclear Safety and Security
Department of Safeguards
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

GUIDANCE FOR THE EVALUATION OF INNOVATIVE
NUCLEAR REACTORS AND FUEL CYCLES:
REPORT OF PHASE 1A OF THE INTERNATIONAL PROJECT ON
INNOVATIVE NUCLEAR REACTORS AND FUEL CYCLES (INPRO)
IAEA, VIENNA, 2003
IAEA-TECDOC-1362
ISBN 92–0–105503–X
ISSN 1011–4289

Printed by the IAEA in Austria
June 2003

FOREWORD

The IAEA General Conference in 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. Resolutions of the UN General Assembly in 2001 and 2002 provided additional endorsement for INPRO, by emphasizing the unique role that the IAEA can play in developing user requirements and in addressing safeguards, safety, and environmental questions for innovative reactors and their fuel cycles and stressing the need for international collaboration in the development of innovative nuclear technology.

This report documents the results of the first phase of INPRO, Phase 1A, that ended in June 2003. The INPRO Steering Committee endorsed publication of the report at its 5th meeting, held in Vienna, 26–27 May 2003.

It is expected that during the following phases of INPRO corresponding reports will be generated at appropriate intervals.

The IAEA highly appreciates the guidance and advice received from the participants listed at the end of this report and the valuable comments made by the Steering Committee at its five meetings held in Vienna. The IAEA would also like to express its thanks to C. Allan (Canada), F. Depisch (Germany) and N. Rabotnov (Russian Federation) for editing the report and to R. Duffey (Canada), A. Gagarinski (Russian Federation) and F.H. Hammad (Egypt) for performing a peer review on the final draft of the report.

The project was implemented under the IAEA Project Manager V.M. Mourogov and the Project Co-ordinator J. Kupitz of the Department of Nuclear Energy.

CONTENTS

SUMMARY

In 2000, the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles, referred to as INPRO, following a resolution of the General Conference (GC(44)/RES/21). Earlier, the President of the Russian Federation, at the Millennium Summit, called upon IAEA Member States to join their efforts in creating an innovative nuclear power technology to further reduce nuclear proliferation risks and resolve the problem of radioactive waste. As of April 2003, INPRO had 15 members: Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Republic of Korea, Pakistan, Russian Federation, Spain, Switzerland, the Netherlands, Turkey and the European Commission.

The main 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.

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, co-operation 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 of the calibre and size needed to support a truly substantial nuclear contribution to global energy supplies.

To set out the boundary conditions for the desired innovations of nuclear energy systems, INPRO established several task groups to define:

- *Prospects and Potentials* of nuclear power within the next 50 years;

- *User Requirements* for innovative nuclear energy systems (INS) in the area of *Economics*, *Sustainability* and *Environment, Safety, Waste Management, Proliferation Resistance,* and *Cross Cutting Issues; and*

- *Methodology for Assessment* of INS.

Having completed these tasks, it is planned that several Member States will apply the INPRO methodology to make a judgement on the potential of INS under consideration for development, to specify corresponding research, development and demonstration (RD&D) needs for their development, and to identify improvements in the methodology.

The results achieved as of the end of April 2003 are summarized briefly below and in more detail in the full text of this report. It is intended to issue separately the working material on which this report is based and which was produced at a number of consultancy meetings held during the course of the Project.

In the area of *Prospects and Potentials* of nuclear power, three topics are briefly discussed: past developments and the current role of nuclear energy, issues surrounding the use of nuclear power, and the potential role of nuclear energy systems in meeting the demand for energy in the 21st century. Early developments in civilian nuclear power were characterized by the need to keep pace with the high energy growth rates of the post-war period, which gave rise to ambitious plans for thousands of GW(e) of nuclear capacity to be installed by the end of the 20th century. But the deployment of nuclear power slowed, primarily because of a decline in the growth of energy demand in the developed countries. Other factors, such as serious accidents at Three Mile Island and Chernobyl and concerns about the long-term management of spent fuel and high level waste, and about nuclear proliferation, also contributed.

While expansion of the number of plants has slowed, one very significant recent development has been the steady improvement in availability factors, equivalent to the construction of about 33 new nuclear power plants. The result is that nuclear power has retained its 16% share of global electricity production. Currently, new additions to nuclear capacity are centred in Asia, but signs of revitalization in western Europe and in North America are visible.

The results of a Special Report on Emission Scenarios (SRES), commissioned by the Intergovernmental Panel on Climate Change (IPCC) in 1996, and published in 2000, have been used to examine the expectations and potential for nuclear energy in the 21st century. The SRES presents 40 reference scenarios, grouped according to four storyline families, extending to 2100. Global primary energy grows between a factor of 1.7 and 3.7 from 2000 to 2050, with a median increase by a factor of 2.5. Electricity demand grows almost 8-fold in the high economic growth scenarios and more than doubles in the more conservational scenarios at the low end of the range. The median increase is by a factor of 4.7. Moreover, nuclear energy plays a significant role in nearly all the 40 SRES scenarios, including the four analysed in this report.

This contrasts with near-term projections by the IAEA, OECD/IEA and US DOE Energy Information Administration that show a declining nuclear share in global electricity production in coming decades, and little or no nuclear movement into energy applications beyond electricity. The difference between these more pessimistic near-term projections and a truly substantial future contribution of nuclear energy – one that takes nuclear's percentage of the world's primary energy supply well beyond today's single digits to 20%, 50% or more – is innovation. Innovation represents the driving force for continuous development of nuclear technologies leading to INS that will be superior to existing plants. These systems comprise not only electricity generating plants, but they also include, e.g., plants (of various size and capacity) for high-temperature heat production, district heating and sea water desalination, to be deployed in developed regions as well as in developing countries and countries in transition.

INS therefore can play an important role in meeting this rapidly expanding world energy demand, consistent with the principle of sustainable development, i.e. meeting the needs of current generations without compromising the ability of future generations to meet their needs. To achieve this objective the issues on which debate concerning the future role of nuclear energy is most often focused need to be addressed. These issues are: economic competitiveness, safety, waste, proliferation resistance and physical protection, and last, but not least, sustainability and environment.

INPRO has examined the needs to be met by innovative nuclear energy systems in each of these areas and has defined a set of *Basic Principles, User Requirements*, and *Criteria* (consisting of an *Indicator* and an *Acceptance Limit*) for each area. *Users* encompass a broad range of groups including investors, designers, plant operators, regulatory bodies, local organizations and authorities, national governments, NGOs and the media, and last not least the end users of energy (e.g., the public, industry, etc). The *Basic Principles, User Requirements* and *Criteria* are set out in detail in Chapter 4 of the report and the *INPRO Methodology* is described in Chapter 5. In the remainder of this executive summary we set out the main messages of these chapters.

In the area of *Economics* four selected scenarios from the SRES study have been analyzed. They cover a variety of possible future developments that are characterized by differing levels of globalisation and regionalization and by differing views of economic growth versus environmental constraints. Provided INS are economically competitive they can play a major role in meeting future energy needs. Economic competitiveness depends on the learning rates (cost reductions as a function of experience) achieved by nuclear energy relative to those of competing technologies. Specific capital costs and electricity production costs 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. These costs should be used with caution since they depend on the learning rates for competing technologies implicit in the SRES scenarios, the discount rates used, and the fact that risks are not taken into account. 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, the energy from INS must remain cost competitive with energy from alternative sources, and INS must represent an attractive investment to compete successfully in the capital market place. To be cost competitive all component costs, e.g., capital costs, operating and maintenance costs, fuel costs, must be considered and managed to keep the total unit energy cost competitive. Limits on fuel costs in turn imply limits on the capital and operating cost of fuel cycle facilities, including mines, fuel processing and enrichment, fuel reprocessing and the decommissioning and long-term management of the wastes from these facilities. Cost competitiveness of energy from INS will contribute to investor confidence, i.e. to the attractiveness of investing in INS, as will a competitive rate of return. As well, meeting the *Principles* and *Requirements* established by INPRO in the areas of safety, waste, sustainability, and proliferation resistance will also contribute to investor confidence.

Internationally there exists strong interest and support for the concept of sustainability, as documented in the report of the Bruntland Commission, the Rio declarations, etc. There is a prima facie case that nuclear power supports sustainable development by providing much needed energy with relatively 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. INPRO has set out two Basic Principles related to *Sustainability*, one dealing with the acceptability of environmental effects caused by nuclear energy and the second dealing with the capability of INS to deliver energy in a sustainable manner in the future. Protection of the environment from harmful effects is seen to be fundamental to sustainability. Adherence to the principle that the present generation should not compromise the ability of future generations to fulfil their needs, requires that the future be left with a healthy environment. Notwithstanding 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, plants and animals; effects on the economy; use/depletion of resources; and cumulative effects resulting from the influence of the system in conjunction with other influences on the environment. Both radiological and non-radiological effects as well as trade-offs and synergies among the effects from 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 (when supplies are limited or quality is under stress) 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 processes, activities and facilities in the energy system at all stages of its life cycle.

In the area of *Safety of Nuclear Installations*, INPRO recognizes that extensive work has been done prior to INPRO to establish safety requirements included in documents such as the Advanced Light Water Reactor Utility Requirements prepared by EPRI, the European Utility Requirements prepared by European Utilities, IAEA Safety Standards Series, e.g., Safety Guides, and INSAG documents. The safety Principles and Requirements developed within INPRO are based on extrapolation of current trends and seek to encompass the potential interests of developing countries and countries in transition. For nuclear reactors, the fundamental safety functions are to control reactivity, remove heat from the core, and confine radioactive materials and shield radiation. For fuel cycle installations, they are to control sub-criticality and chemistry, remove decay heat from radionuclides, and confine radioactivity and shield radiation. To ensure that INS will fulfil these fundamental safety functions, INPRO has set out five Basic Principles but it is also expected that prior work will also be used to the extent applicable.

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 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, using e.g., large scale engineering test facilities including, possibly, pilot plants, 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 development 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.

Because *Waste Management* involves longer time scales and, in many cases, different source terms and pathways, compared with nuclear installations, this topic is dealt with in a separate section of Chapter 4. The already existing nine principles defined by the IAEA for the management of radioactive waste have been adopted by INPRO without modification. 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 interdependencies among steps shall be taken into account. These principles in turn lead to INPRO requirements to specify a permanently safe end state(s) for all wastes and to move wastes to this 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.

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 the 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 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. 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.

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 report should facilitate such harmonization and could make it possible to change the way the production of nuclear energy is regulated. When, for example, the risk 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.

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 innovative energy system, or a component of such a system on a national, regional and/or global basis. The INPRO Methodology is oriented more to identifying a range of technology alternatives that will fulfil Basic Principles and User Requirements set out for INS, rather than to selecting a single best solution. It is recognized that the methodology will need to be applied iteratively, that the INPRO User Requirements and Criteria may be supplemented by additional Requirements and Criteria, e.g., taken from existing Standards and Guides, and that additional work is likely required to elaborate requirements and standards. To assess a given nuclear energy system (or a component thereof) the nuclear energy system and its components are specified together with approaches for meeting all relevant Criteria, User Requirements and Basic Principles. Judgments are then established of the potential of the approaches and their constituent components to meet the Criteria, User Requirements and Basic Principles for the nuclear energy system, and a Judgment of the entire system is arrived at from the Judgments for compliance with all of the Basic Principles, User Requirements, and Criteria. MS must identify all of the fuel cycle components that will be required for the MS to use the component of prime interest to it, e.g., a given design of reactor, and present information on all components so that a holistic view is developed and presented. The rationale for arriving at a given Judgment, i.e. the basis of the Judgment, needs to be developed and explained. The rationale may be based, e.g., on preliminary or detailed safety and environmental analyses, experience with large-scale test facilities or experimental test rigs, extrapolation of experience from similar facilities, the use of expert opinion, and combinations of these. Additional effort will be needed to develop the methodology further for widespread use and to ensure consistency and credibility of the results. Prior to committing to such an effort an assessment of the efficacy of the methodology should be obtained by using it in a number of case studies. It is foreseen that case studies will be performed by individual interested Member States supported by task groups with broader participation of experts from INPRO Member States. To test the methodology, case studies should be carried out for different types of nuclear energy systems, including a global system with components at the preliminary stage of development, a future system that is already reasonably well developed, and systems being considered for application in different regions.

In addition to the recommendations that have already been outlined it is further recommended that Member States define in more detail the RD&D initiatives set out in the report and establish priorities. The IAEA could provide valuable assistance in fostering cooperation among Member States and in co-ordinating joint research programs. The long term objective is to ensure that innovative nuclear energy systems are available to play a major role in meeting the expanding global energy needs of the twenty first century and that their role in doing so is accepted because they are economic, safe, proliferation resistant and sustainable.

CHAPTER 1
BACKGROUND

1.1. Introduction

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”.

At a meeting of senior officials from 25 Member States and international organizations in November 2000, the objectives and implementation of this project were discussed and the Terms of Reference for the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) were finalized.

An International Co-ordinating Group (ICG) has been created to implement INPRO and V.M. Mourogov, Deputy Director General of the IAEA Department of Nuclear Energy, has been appointed as the Project Manager for INPRO (see Figure 1.1 at the end of this chapter).

The project was confirmed by an additional resolution of the IAEA General Conference and by the United Nations General Assembly in 2001 and again in 2002.

1.2. Terms of reference

The Terms of Reference of INPRO, as agreed in November 2000, are reproduced in Sections 1.2.1 to 1.2.6 below.

1.2.1. Rationale

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.

However, the location and availability of technology for the utilization of those resources pose political, economic and environmental challenges, the impacts of which vary between different regions of the world.

The long-term outlook for nuclear energy should be considered in the broader perspective of future energy needs and environmental impact. 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, safety, waste and potential proliferation risks.

At the national level, work on evolutionary and innovative approaches to nuclear energy reactor design and fuel cycle concepts is proceeding in several IAEA Member States. At the international level, OECD/IEA, OECD/NEA and the IAEA are co-operating to review ongoing R&D efforts on innovative reactor designs and to identify options for collaboration. The US Department of Energy is promoting the Generation IV International Forum (GIF) initiative, in which both the IAEA and OECD/NEA are participating as observers.

While existing national and international activities on innovative approaches play an important role, they are in most cases more limited in terms of scope, participation or timeframes. Against this background, and taking account of the Agency’s unique mandate in the fields of nuclear technology, safety and safeguards, the IAEA General Conference has 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". The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is a response to that invitation.

1.2.2. Overall objectives

The overall objectives of INPRO are:

- To help to ensure that nuclear energy is available to contribute in fulfilling, in a sustainable manner, 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.

1.2.3. Implementation strategy

The Project will be an Agency-wide project, with contributions from all relevant IAEA Departments within available resources.

The framework for implementation of the Project will consist of the following:

- A Steering Committee, comprising as members, senior officials from Member States that participate through provision of extra-budgetary resources and, as observers, representatives from interested Member States and international organizations. IAEA project management will also be represented. The Steering Committee will meet as appropriate to provide overall guidance, advise on planning and methods of work and review the results achieved;
- An International Co-ordinating Group (ICG), comprising cost-free experts from participating Member States, which will co-ordinate and implement the project;
- Technical Expert Groups, comprising experts from Member States, which will be convened as appropriate by the ICG to consider specific subjects;
- Support from the IAEA, including project management, administrative and technical support.

The Project will be implemented in two phases. Phase I will be initiated in early 2001 as soon as sufficient resources are made available. Results of the first phase and plans for the second phase will be subject to review and approval by the Steering Committee.

The Operating Guidelines for the ICG are set out in the Attachment to this document (see Section 1.2.6).

1.2.3.1. Phase I – guidelines, methodology and review

In the first phase, work will proceed in five subject areas recognized as important for the future development of nuclear energy technology, and on two parallel tracks.

The five subject areas are:

- Resources, Demand and Economics;
- Safety;
- Spent Fuel and Waste;
- Proliferation Resistance;
- Environment.

The two tracks are:

- Track 1: selection of criteria and development of methodologies and guidelines for the comparison of different concepts and approaches, taking into account the compilation and review of such concepts and approaches; and determination of user requirements in the subject areas.
- Track 2: examination of innovative nuclear energy technologies made available by Member States against criteria and requirements.

ICG will seek input from the on-going Three-Agency Study (jointly conducted by OECD/IEA, OECD/NEA and IAEA) on "RD&D on Innovative Nuclear Reactors – Status and Prospects" and will interact with other national and international stakeholders, in particular with OECD/NEA and Generation IV International Forum (GIF), in order to ensure effective co-ordination and co-operation in a complementary manner.

The Steering Committee will review the results of Phase I and recommend, based upon a proposal to be developed by ICG, actions for follow-up, intended to continue to meet the interests of IAEA Member States. These results and recommendations will be reported to IAEA Member States, as appropriate.

1.2.3.2. Phase II

Upon successful completion of the first phase, taking into account advice from the Steering Committee, 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.

1.2.4. Resources

The Project will be implemented using mostly extrabudgetary resources offered by interested Member States. Contributions to implementation of the Project may be both in kind and in cash.

1.2.5. Partners

The following parties are considered important partners for the implementation of the project:

- Participating Member States;
- Interested Member States;

- Interested international organizations;
- Interested national and international institutions.

Partners will be invited to participate and/or contribute as appropriate to the project.

1.2.6. Operating guidelines (Attachment A to the TOR)

These Operating Guidelines, made pursuant to the TOR for INPRO will guide the operations of the ICG.

ICG will be set up for an initial period of two years and will be composed of cost-free experts, provided by participating Member States.

The experts of ICG should have broad expertise in the areas of nuclear energy and fuel cycle technology, nuclear safety, economics and nuclear proliferation resistance.

The experts of ICG will also liase with home teams in their countries and/or organizations.

ICG will be constituted according to the administrative rules of the IAEA and will report directly to the Project Manager.

ICG activities will be implemented using mostly extra-budgetary funds.

The IAEA will provide secretarial support to ICG, supply relevant in-house information, and co-operate fully with it in order to facilitate implementation of the Project and to achieve its objectives.

Objectives and results to be achieved are outlined in the TOR of the Project. More detailed working plans and schedules will be drafted by ICG and the IAEA for approval by the Steering Committee.

1.3. Current status

As of April 2003 INPRO had 15 members:

Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Republic of Korea, Pakistan, Russian Federation, Spain, Switzerland, the Netherlands, Turkey and the European Commission.

In total, those members have nominated 19 Cost Free Experts (CFE) to work on INPRO at the IAEA headquarters in Vienna for periods of 3 months to 3 years. These experts have broad expertise in the areas of nuclear energy and fuel cycle technology, nuclear safety, economics, waste management, and nuclear proliferation resistance, and form the International Co-ordinating Group on Innovative Nuclear Reactors and Fuel Cycles (ICG). Together with the IAEA secretariat, the ICG has the principal operational responsibility for the implementation of INPRO. In total, more than 14 person years have been spent on the project as of the end of April 2003.

The IGC has organized several consultancies at the IAEA, thereby profiting from the expertise of the participating experts.

During the course of the project it became clear that, in addition to the five subject areas set out in Section 1.2.3.1, issues that cut across these subject areas, i.e. cross cutting issues dealing with infrastructure, socio-economic considerations, knowledge retention, etc should also be examined. As well, in examining the original five subject areas it was found convenient to re-group them, and include crosscutting issues and the methodology for assessment of innovative nuclear energy systems as follows:

- Prospects and potentials (Resources and demand) of nuclear power;
- Economics;
- Sustainability and Environment;
- Safety of Nuclear Installations;
- Waste Management;
- Proliferation Resistance;
- Cross Cutting Issues; and
- Methodology for Assessment.

The two tracks defined in the TOR also became known as INPRO Phase 1A, and Phase 1B, respectively.

In addition to the continued use of CFEs located at the IAEA, it is planned to support the project by defining external work packages and case studies for INPRO member states (MS), which can be elaborated within the home offices of the MS. A work package will consist of a defined scope of work in a specific area and will involve as a minimum 3 person-months of work. The case study will take an existing (planned) innovative nuclear energy system and evaluate it against the User Requirements defined within INPRO.

During Phase 1A the need for RD&D has been identified. It is anticipated that these needs will be further elaborated and prioritized in Phase 1B.

Since 2001 INPRO has been implemented using mostly extra-budgetary resources provided by interested Member States.

1.4. INPRO and how it relates to other international activities

INPRO seeks to interact with other national and international stakeholders and initiatives, e.g., with the Generation IV International Forum (GIF) and the OECD, to ensure effective co-ordination with these groups and to co-operate with them in a complementary manner. INPRO has benefited from the Three-Agency Study, a study jointly conducted by OECD/IEA, OECD/NEA and the IAEA on “Innovative Nuclear Reactor Developments – Opportunities for International Co-operation” [1-1]. The advanced nuclear systems evaluated in the Three-Agency Study present an excellent basis for first applications of the INPRO results in later phases of the project.

The IAEA is represented in GIF [1-2] as an observer, at the Policy and Experts Groups, and their experts participate in the technical meetings of GIF. Furthermore there are ongoing contacts between the IAEA and GIF to enhance the synergy between the two projects.

Within the international community, INPRO’s unique status is attributed to the following considerations:

- Scope: INPRO is examining the major challenges to be addressed and the requirements to be met to facilitate large-scale nuclear energy development globally, including developing countries. INPRO is looking at the whole range of innovative nuclear technologies for both reactors and fuel cycles, and considers both technical and institutional and infrastructure aspects. Requirements are being developed with respect to economics, sustainability and environment, safety, waste management and proliferation resistance.

- IAEA Mandate: INPRO was initiated through a resolution of the IAEA General Conference and received its mandate from IAEA Member States. Thus, INPRO is established as an open process, and access to results is given to all IAEA Member States. As well, the IAEA's established Technical Working Groups can assist with review, discussion and the promotion of collaborative research.
- Motivation: INPRO aims at integrating views from all stakeholders, notably from both nuclear technology developers and nuclear technology end users, including those in developing countries, and taking into account regional energy demand and supply patterns. The development of user requirements with the participation of end users and their participation in case studies of comparative assessments are an essential element in the first phase of INPRO.
- Time horizon: The time horizon covers the next five decades. Energy scenarios for the period envisaged may evolve in any of several different directions but the demand for energy and the use of electricity are expected to increase substantially in most scenarios. As well, new needs such as the use of hydrogen as an energy carrier and seawater desalination for the production of potable water will have to be considered.
- Proliferation resistance: The unique mandate of the IAEA in the area of safeguards helps to promote an international consensus with respect to proliferation resistance and a systematic assessment of proliferation resistant features and measures.

References to Chapter 1

[1-1] OECD INTERNATIONAL ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL NUCLEAR ENERGY AGENCY, Innovative Nuclear Reactor Development Opportunities for International Cooperation, OECD/IEA, Paris (2002).

[1-2] UNITED STATES DEPARTMENT OF ENERGY Nuclear Energy Research Advisory Committee and the GENERATION IV INTERNATIONAL FORUM, A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF002-00, (December 2002), (http://www.doe.ne.gov).

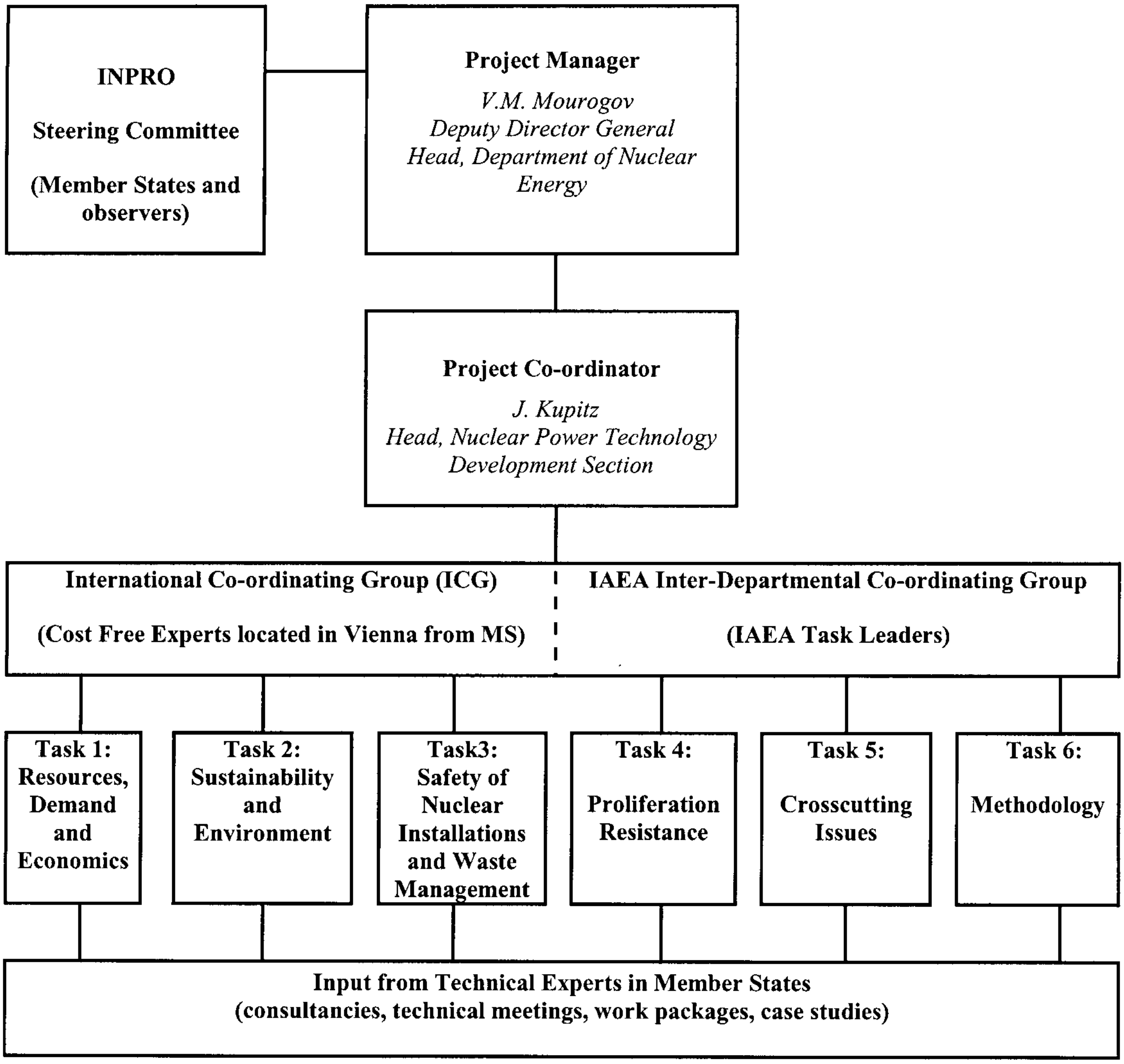


Figure 1.1. Organization of the INPRO project.

CHAPTER 2
NUCLEAR POWER PROSPECTS AND POTENTIALS

2.1. Past developments and current role

2.1.1. Past developments[1]

While the development of nuclear reactor technology was initially driven by military applications, such as plutonium production for weapons and the development of light water reactors for nuclear-powered submarines, there was a clear recognition of the potential for nuclear technology to supply the energy needs of future generations and strong ethical and political interest in peaceful applications of the technology. The first civilian reactors for electricity production were fuelled with ^{235}U, using fuel cycle capabilities developed for the military sector. While the first civilian nuclear power facilities operated successfully, potential shortages of uranium were a long-term concern. But it was recognized that the energy potential of uranium resources could be multiplied using nuclear breeding and that, with breeding, uranium and thorium resources offered an essentially inexhaustible fuel resource. These considerations led to the strategy of further development to proceed in two stages:

1) The use of thermal once-through reactors to generate energy and to accumulate plutonium for the start-up of advanced fuel cycles and breeder reactors, being developed concurrently, e.g., fast reactors; and

2) The deployment of breeder reactors[2] and advanced fuel cycles to support large-scale growth of nuclear power to replace, over time, traditional fossil energy sources.

Thermal, once-through reactors use less than 1% of the energy potential of natural uranium. At the same time, the potential land-based resources of cheap uranium suitable for such reactors (currently assessed at about 10^6 Mg out of 10^{14} Mg found in the Earth’s crust) are smaller than the reserves of oil and gas and much smaller than those of coal. Thus, the strategic objective was to secure an inexhaustible resource of cheap fuel through nuclear breeding of uranium and possibly thorium. The short-term tactic was to use ^{235}U-fuelled thermal reactors to produce energy and radioisotopes for immediate civilian purposes and to accumulate energy-grade plutonium for use in advanced fuel cycles and reactors.

Two factors had a strong effect on the early development of nuclear power:

- The challenge of keeping pace with the high energy growth rates, globally ~5 to 7% per year, in the post-war decades; and

- The successful adaptation of military nuclear technologies for civilian application in the first nuclear power plants.

---

[1] This section is based on material documented in the Russian White Book of Nuclear Power and edited by the IAEA [2-1].

[2] The main strategic requirement for fast breeder reactors was a short plutonium doubling time. A target time of 6 to 8 years (even lower figures were mentioned in some cases) was to be achieved as a result of large breeding ratios and a high fuel power density. This necessitated an uranium blanket, a light heat-conducting coolant (Na), and a reduced period of irradiated fuel cooling prior to reprocessing (e.g., 0.5 to 1 year instead of the usual 3 years). In the first fast reactors, use was made of the well proven oxide fuel but such fuel has a low density and low heat conductivity and therefore could not provide the large breeding ratios and high power densities needed to achieve the targeted doubling time. The development of high-density and highly heat-conductive monocarbides, mononitrides and metal alloys of U and Pu were seen as the long-term solution.

These factors give rise to ambitious plans for thousands of GW(e) of nuclear capacity by the end of the 20th century but the rapid growth of nuclear power eventually slowed as the growth of energy demand decreased. Nevertheless, as a result of progressive improvements in the designs of thermal reactors, the economic competitiveness of nuclear power plants (NPPs) was maintained, so that the global fleet of nuclear power plants grew, by the early 1980s, to about 300 operating nuclear reactors with a total installed capacity of ~200 GW(e) and to about 400 plants by the 1990s. An important contributor to such impressive growth was substantial governmental investment.

The plans for continued rapid expansion of nuclear power on a global scale during the 20th century proved to be overly ambitious and the need to deploy advanced fuel cycles and breeder reactors receded into the future. Some countries, therefore, started to use plutonium, recovered from processing used fuel from once-through reactors, in the form of mixed-oxide fuel. While it can be argued that the primary reasons for the slow down in the deployment of nuclear power were the slow down in the growth of energy demand and, for fast reactors, the availability of cheap uranium, other factors certainly contributed, including:

- Serious accidents at Three Mile Island in the USA and Chernobyl in the USSR, which brought to light important safety concerns;

- The significantly higher cost of fast reactors relative to that of thermal reactors;

- Concerns about the long term management of spent fuel (open fuel cycle) and high level waste (from reprocessing, closed fuel cycle) and the absence of a demonstrated solution; and

- Continued concern about nuclear (weapons) proliferation, despite the success of the safeguard activities of the IAEA.

While the deployment of fast reactors has been suspended and the growth of nuclear power has slowed, nuclear power is now a well established energy technology that is making an important contribution to global electricity and energy production. As well, significant progress has been made in addressing issues of concern:

- The problem of fuel resources has been addressed by *increasing* the production of relatively cheap uranium, thus avoiding the need and cost of closing the nuclear fuel cycle;

- The short-term problem of waste management was dealt with by *expanding* irradiated fuel storage facilities while the technologies for long-term waste management, e.g., geological disposal, are being developed and demonstrated;

- Lessons learned from the Three Mile Island and Chernobyl accidents have been incorporated through improvements in safety culture and defence-in-depth to address both the most probable (design-basis) and severe (beyond design basis) accidents; and

- The proliferation problem has been addressed by *stepping up* international monitoring of fissile materials.

Hence, today, nuclear power is recognized as a mature industrial technology with a track record of success and good prospects for the future. But public concerns about safety, waste management, and nuclear proliferation persist and need still to be resolved.

2.1.2. Current role[3]

Worldwide there were 441 operating nuclear power plants (NPPs) at the end of 2002 supplying 16 percent of global electricity generation. In 2002, 20% of the USA's electricity was nuclear, 27% of Spain's, 31% of Germany's, 34% of Japan's, 39% of the Republic of Korea's, 44% of Sweden's, and 77% of France's. Cumulative operating experience now stands at over 10,000 reactor-years. Six new NPPs were connected to the grid in 2000, three in 2001, and six in 2002. Table 2.1 summarizes world nuclear experience as of the end of 2002.

Looking ahead to nuclear power's prospects in the new century, four features stand out:

1) New nuclear power plants are not being built fast enough to maintain nuclear power's 16% share of global electricity generation;

2) Current expansion, as well as near-term and long-term growth prospects, is centred in Asia;

3) The year 2002 saw some signs of revitalized growth in Western Europe and North America, where growth has stagnated because of economics, market liberalization, and excess capacity; and

4) Long-term projections for nuclear power, particularly in the event of international agreement to significantly limit greenhouse gas (GHG) emissions, are more bullish than near-term trends. While economics is a key factor, public concerns about safety, waste, sustainability, and proliferation will need to be addressed.

The most significant recent trend has been that of steady increases in availability factors. The cumulative impact of such increases since 1990 is equivalent to having built 33 new NPPs, each of 1000 MW(e). Without such improvements in availability factors, nuclear power would not have maintained its 16% share of global electricity.

Currently, growth is centred in Asia. Of 33 reactors currently under construction worldwide, 20 are located either in China, Taiwan, China, the Republic of Korea, the Democratic People's Republic of Korea, Japan, or India. Seventeen of the last 26 reactors to be connected to the grid are in the Far East and South Asia. And the greatest growth in nuclear electricity production in 2001 occurred in Japan.

Within Asia, capacity and production are greatest in Japan (54 NPPs) and the Republic of Korea (18 NPPs). Both countries lack indigenous energy resources, and consequent concerns about diversity and security of energy supply and stability of energy costs in the face of currency fluctuations make the economics of new NPPs more competitive. Seven NPPs are in operation in China; four more are under construction. Taiwan, China has six NPPs with two more under construction. India has 14 small NPPs (up to 220 MW(e)) operating, and eight under construction).

---

[3] This section is based on material documented in the IAEA Nuclear Technology Review 2002 [2-2].

Table 2.1. Nuclear Power Reactors in Operation and Under Construction in the World (as of December 2002)

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2001		Total Operating Experience	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW(e)·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	6.54	8.19	48	7
ARMENIA	1	376			1.99	34.82	35	3
BELGIUM	7	5,760			44.1	58.03	184	7
BRAZIL	2	1,901			14.35	4.34	23	3
BULGARIA	4	2,722			18.24	41.55	125	2
CANADA	14	10,018			72.35	12.85	461	2
CHINA	7	5,318	4	3,275	16.68	1.14	31	6
CZECH REPUBLIC	6	3,468			14.75	19.76	68	10
FINLAND	4	2,656			21.88	30.54	95	4
FRANCE	59	63,073			401.30	77.07	1,287	2
GERMANY	19	21,283			162.30	30.52	629	1
HUNGARY	4	1,755			14.13	39.09	70	2
INDIA	14	2,503	8	3,610	17.32	3.72	209	5
IRAN			2	2,111			0	0
JAPAN	54	44,287	3	3,696	321.94	34.26	1,070	4
KOREA DEM. PEOPLES REP. OF			1	1,040			0	0
KOREA REPUBLIC OF	18	14,890	2	1,920	112.13	39.32	202	7
LITHUANIA	2	2,370			11.36	77.58	34	6
MEXICO	2	1,360			8.11	3.66	21	11
NETHERLANDS	1	450			3.75	4.16	59	0
PAKISTAN	2	425			1.98	2.86	33	10
ROMANIA	1	655	1	655	5.05	10.46	6	6
RUSSIAN FEDERATION	30	20,793	3	2,825	125.36	15.40	731	4
SOUTH AFRICA	2	1,800			13.34	6.65	36	3
SLOVAKIA	6	2,408	2	776	17.10	53.44	97	0
SLOVENIA	1	676			5.03	38.98	21	3
SPAIN	9	7,574			61.07	26.88	210	2
SWEDEN	11	9,432			69.20	43.85	300	1
SWITZERLAND	5	3,200			25.29	35.96	138	10
UNITED KINGDOM	31	12,252			82.34	22.44	1,301	8
UKRAINE	13	11,207	4	3,800	71.67	46.36	266	10
UNITED STATES OF AMERICA	104	98,230			768.83	20.35	2,767	8
Total	441	358,661	33	27,100	2,543.57		10,696	4

Note: The total includes the following data in Taiwan, China:
— 6 units, 4,884 MW(e) in operation; 2 units, 2,700 MW(e) under construction;
— 34.09 TW(e)·h of nuclear electricity generation, representing 21.57% of the total electricity generated there;
— 128 years 1 month of total operating experience.

In the USA, there is currently no construction. The key development has been market liberalization, which has prompted consolidation, acquisitions, upratings, and licence extensions. The average availability factor rose from 72% in 1990 to 90% in 2001, and nuclear generation costs dropped to record lows. The US Nuclear Regulatory Commission (NRC) has granted licence extensions, to 60 years, to fourteen US reactors, and sixteen more applications are under review. In Canada, near-term nuclear expansion will result from restarting a number of the eight nuclear units that are currently laid up and work to do so is under way.

Western Europe has 146 reactors. Overall capacity is likely to remain near existing levels, even with long-term nuclear phase-outs planned in Belgium, Germany and Sweden. The most significant possibility for new nuclear capacity is in Finland. In May 2002 the Finnish Parliament ratified the Government's favourable "decision in principle" on Teollisuuden Voima Oy's (TVO's) application to build a fifth Finnish NPP. In September 2002 TVO invited bids from reactor vendors.

Eastern Europe and the economies in transition have 68 operating NPPs. Ten more are under construction. In the Russian Federation, there has been an increase of nuclear electricity production of 30% since 1998, thus ending the stagnation following the Chernobyl accident. Most of this increased production has resulted from increased plant availability.

In Latin America there are six operating NPPs and one under construction. Two NPPs are operating in South Africa.

2.2. Issues surrounding the use of nuclear power

2.2.1. Introduction

It is a fact, often overlooked, that nuclear energy exists or is expanding in 31 countries, which represent 2/3rd of the world's population. A minority of countries (e.g., Belgium, Germany and Sweden) at the moment have policies to phase out, in the long term, nuclear power. In Austria, Denmark, Greece, Ireland, Italy[4] and Norway nuclear power is banned, but the import of electricity produced by nuclear power is not. These policies reflect issues of political and public acceptance for nuclear power that do not apply to other energy sources, none of which faces categorical restrictions comparable to those that these countries apply to nuclear power. Nuclear power's special political and public acceptance issues are discussed below. The issues on which debate is most often focused are six: economic competitiveness, safety, waste management, proliferation resistance, physical protection and last but not least, sustainability.

2.2.2. Economic competitiveness

Most of the world's electricity markets are now moving towards greater competition, driven in part by technology, and in part by the experience that competitive markets are more self-sustaining. Well managed existing nuclear power plants have generally fared well in restructured markets. Operating costs of NPPs, including fuel costs, are usually lower than the costs of alternatives, with the exception of hydroelectricity.

Capital is largely depreciated, and a plant with operating and maintenance costs below market prices turns a profit. Nuclear production costs in the USA have dropped to an average of

---

[4] Formally speaking Italy is under a moratorium.

1.83 cents/kW(e)·h in 1999 and 1.74 cents/kW(e)·h in 2000, with the most efficient plants operating at costs around 1.2 cents/kW(e)·h. Nuclear generation costs have also dropped in the United Kingdom from 1.99 pence/kW(e)·h to 1.87 pence/kW(e)·h in 2000. For Electricité de France they dropped 7% between 1998 and 2000 to 15-18 centimes/kW(e)·h, depending upon the site. Production costs have also decreased in Canada. This downward trend in production cost is expected to continue.

Almost all nuclear plants that are economically competitive have made significant if not dramatic improvements over the last decade in their availability and operating costs. Individual plant availability increased in many cases by some 30 percentage points. Global energy availability increased from 73% to over 83% in 2001 – the equivalent of adding 33 GW(e) of new generating capacity. In the USA the energy availability factor rose steadily from about 80% in the late eighties to 90% in 2001. The average energy availability factors in Germany, Spain, Finland, Brazil, the Republic of Korea and the Netherlands all exceeded 90% in 2001.

For all these reasons (and because of the high capital cost of new NPPs discussed immediately below), there is growing interest in licence renewals. Fourteen US NPPs have been granted licence renewals that increase the licensed lifetime of each to 60 years. An additional 40% of operating US plants have indicated an intention to seek licence extensions, and the Nuclear Regulatory Commission (NRC) expects the figure to eventually reach 85% or higher. In the Russian Federation, Rosenergoatom has begun a program to extend licences at eleven NPPs. For Novovoronezh-3, Rosenergoatom received a five-year licence extension (beyond the original 30-year licence period) in December 2001. In 2002, it submitted an application for a 15-year extension for Novovoronezh-4 and is currently preparing applications for 15-year extensions for Kola-1, Bilibino-1 and Leningrad-1.

Applications for power upratings are motivated by many of the same factors. In 2001 upratings calculated from IAEA PRIS[5] data totalled approximately 740 MW(e), with the bulk occurring in North America (about 510 MW(e)) and Western Europe (about 180 MW(e)). The US NRC expects applications for 1600 MW(e) worth of upratings over the next five years.

Managing the financial risks associated with the high capital costs of NPPs, which account for some 70% of total nuclear generating costs, is a major challenge in the financing and building of new NPPs. Recently constructed NPPs have generally cost two to four times more to build than fossil-fuelled plants, but two qualifiers should be kept in mind. First, although capital cost and generating cost estimates are generally higher for nuclear than other sources, there is enough overlap to make nuclear sometimes the preferred option, particularly in terms of generating costs. Second, the situation is different in different parts of the world. Thus, nuclear power is more competitive in Japan and the Republic of Korea, where fossil fuel prices are high, and high priority is given to energy supply security. This is an important factor in most recent decisions to build new nuclear power plants (e.g., in China, India, Japan and the Republic of Korea), just as it was earlier in countries like France, Germany and Sweden. Nuclear power also plays an important role in Japan's, Canada's and (partly) in Europe's plans for meeting its Kyoto Protocol commitment to reduce greenhouse gas emissions.

---

[5] Power Reactor Information System of the IAEA.

2.2.3. Safety

Comparative assessments of the health and environmental risks of different electricity generation systems show that nuclear power and renewable energy systems are at the lower end of the risk spectrum. None-the-less, the consequences (health effects, wide spread contamination) of major accidents, such as the 1986 Chernobyl accident, remain a concern, especially for plants located close to major population centres. The Chernobyl accident resulted from a combination of serious design flaws, and a lack of regulatory control, coupled with serious operator mistakes. Since the accident, there have been major improvements in the safety of nuclear power plants through the enhancement of the nuclear safety culture and the application of advanced technology to improve engineered safety features. The global safety record for nuclear power plants has shown continued improvement, with marked progress in the safety-driven modernization of reactors in Central and Eastern Europe. Also, since the Chernobyl accident, the comprehensive exchange of information on operational safety experience has become a major factor in nuclear safety improvements worldwide. International mechanisms to facilitate exchange include the World Association of Nuclear Operators (WANO) and the IAEA. WANO was created in the aftermath of the Chernobyl accident to foster information exchange, comparison, emulation of best practice and communication among its members. Substantial safety improvements in nuclear power plants have been recently reported by WANO, e.g., the number of unplanned automatic scrams has decreased by 67% in the time period from 1990 to 2000.The IAEA's activities include safety review and assessment missions, the establishment of internationally recognized safety standards and requirements and activities within the Convention on Nuclear Safety.

The broad acceptability of current reactor safety levels is demonstrated by the continued successful operation of reactors all over the world. The safety debate today is largely in the context of the European Union's efforts to accelerate closure of first-generation water-cooled WWER and graphite-moderated RBMK reactors in Eastern Europe. As with other technologies (e.g., aeroplanes, automobiles and buildings in earthquake zones), new ideas and engineering advances mean that there will always be room for safety improvements. Thus, even with the broad acceptability of today's NPP safety levels, continuing innovation and safety advances will remain an essential objective of all new reactor and fuel cycle designs.

2.2.4. Waste management

A major political and public acceptance issue today is the disposal of spent fuel and high-level waste (HLW). The preferred approach in most countries is geologic disposal using a combination of natural and engineered barriers to isolate the wastes from the surface environment for many thousands of years. Countries have taken a range of approaches in developing and demonstrating the technology for disposal and in identifying potential sites. Significant progress has been made in a number of countries. In the USA, the Waste Isolation Pilot Plant (WIPP) began receiving military transuranic waste for permanent disposal in 1999. In February 2002 President Bush approved proceeding with the Yucca Mountain disposal site. Congress effectively ratified that decision by voting in July to override formal objections by the State of Nevada. According to the current schedule, the Yucca Mountain repository should be completed by 2010.

In December 2000, the Finnish Government approved an application for a decision "in principle" filed by Posiva, the nuclear waste company, to build a final repository for spent fuel in a cavern near the nuclear power plants at Olkiluoto. The Parliament ratified the decision in May 2001. In addition, separate construction and operating licences, issued by the Government, will be required. Construction would start in 2011 and operation about ten years later. In May 2002, when Parliament ratified the decision in principle for a fifth Finnish NPP, it also ratified a separate decision in principle so that spent fuel from the new reactor could also be deposited at Olkiluoto. In Sweden two (of six original) candidate communities have been selected for, and have agreed to, detailed geological investigations for a waste repository. These should begin in 2002 and run for five or six years. The Swedish nuclear fuel and waste management company, SKB, hopes to make a final site proposal by about 2007.

Countries currently developing geologic repositories for high-level waste disposal have generally adopted a stepwise approach that includes a period of intensive underground investigations and testing. Since it is expensive and time-consuming to develop such facilities, there is interest in using national underground research facilities as international training centres and the IAEA is working to create an international network of centres of excellence for training scientists from Member States with limited resources. The IAEA has also published Safety Standards and Guides for waste disposal. See, for example, Refs [2-3] and [2-4].

Research continues on methods to reduce the quantities of long-lived radionuclides in high-level wastes from reprocessing through new techniques to reduce actinide generation and to transmute long-lived radioactive wastes. Discussion also continues on the role of the retrievability of wastes from geological repositories after emplacement. Recognizing that wastes can be retrieved after emplacement offers the possibility of being more responsive to future changes in technology and social preferences**.**

2.2.5. Proliferation resistance

The international non-proliferation regime consists of the Treaty on the Non-Proliferation of Nuclear Weapons and comprehensive IAEA safeguards agreements as described in INFCIRC/153 [2-5], including additional protocols (INFCIRC/540 [2-6] now in force in 30 countries, international verification measures (the IAEA safeguards system plus regional agreements and bilateral agreements) and export controls (administered by the Nuclear Supplier Group). States that have not signed the NPT have INFCIRC/66 [2-7] safeguards agreements covering some of their nuclear activities. In addition to maintaining an effective and efficient safeguards system, the technical challenge is to design new nuclear facilities even less attractive for proliferation.

2.2.6. Sustainable development and environmental protection

As has been indicated, with the use of advanced fuel cycles and breeder reactors, nuclear fission reactors offer the possibility of meeting the world’s energy needs for millennia. Thus, from the very beginning in most countries, nuclear energy was seen to be a sustainable source of energy. Further, nuclear energy sources do not emit green-house gases nor gases that lead to the production of acid rain, and under normal operating conditions, emissions of all types are small. Thus, there is a *prima facie* case that nuclear power supports sustainable development by providing much needed energy with relatively low burden on the atmosphere, water, and land use. Further deployment of nuclear power will help to alleviate the environmental burden caused by other forms of energy production, particularly the burning of fossil fuels.

The definition of sustainable development that is widely accepted is that put forward in the Brundtland Report, namely, “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Implementation of sustainable development is, however, an on-going political process and a matter of international negotiation. At the meeting of the United Nations Committee on Sustainable Development in April of 2001, nations concluded that sustainability is a matter for individual nations to define in the light of their own interests and that the sustainability of nuclear power was also a matter of national policy.

The focus of concern about particular aspects of sustainable development will vary by region and by income level. For some developing countries, access to commercial energy is a key concern while in others affordability is the issue rather than access. In more developed countries, pollution abatement and protection of the environment are more important. For most of the world the key issue is economic development, which is seen, to be a necessary condition for achieving a better standard of living, improved health, and a cleaner environment.

Protection of the environment from harmful effects is seen to be fundamental to sustainability. Adherence to the principle that the present generation should not compromise the ability of future generations to fulfil their needs, requires that the future be left with a healthy environment. Notwithstanding 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. Moreover, efficient and effective use of resources will be necessary for a nuclear energy system to fulfil its long-term potential.

The safety of facilities and operations is also vital to environmental protection and hence to the sustainability of nuclear energy and to its use to meet the goal of sustainable development. Safety, in the sense traditionally used in the nuclear industry, addresses, almost exclusively, radiological effects on humans and the risk of nuclear accidents with the potential to release radioactive material. The scope of environmental aspects is much broader, including potential effects on non-human environmental components and effects of non-radiological stressors. Moreover, the standards and method employed in evaluating and managing environmental effects are generally different from those used in establishing nuclear safety. Thus, nuclear safety can be thought of as only one component, albeit an important one, of environmental protection and sustainability.

To be sustainable an energy source must be economic. But to properly evaluate the economic viability and comparative economic advantage of a given energy technology, it is imperative that all costs of the technology be considered. This will include the costs associated with protecting human health and the environment, such as any control measures that must be incorporated in facility design and operation. Moreover, the so-called external costs, those born by society because of residual health and environmental effects, but not charged to the producer, should also be included. In the past, many of these costs have been left unaccounted for when estimating the total unit cost of production. For example, industries, in general, have not been charged the cost to society associated with their use of the atmosphere as a repository for their toxic waste products. The failure to “internalise” costs such as this is increasingly recognized and the economics of future technologies should include environmental costs, quantified and internalised to the extent practicable. In this context, management of wastes, and in particular the long-term management of radioactive wastes is an important consideration.

Finally, the question of nuclear proliferation is also of concern when considering the role of nuclear energy in sustainable development. So, safety, economics, waste management, environmental protection and proliferation resistance are all important aspects that need to be addressed when considering the future role of nuclear energy and innovative nuclear energy systems.

2.2.7. Physical protection of nuclear material and facilities

The recommendations presented in the IAEA document INFCIRC 225/Rev.4 (Corrected) [2-8] reflect a broad consensus among Member States on the requirements, which should be met by systems for the physical protection of nuclear material and facilities. The principles and objectives derived from this document should be taken under consideration during the design of future nuclear facilities. Additional guidance is provided in Refs [2-9] and [2-10].

Physical protection should be based on a graded approach and should take into account:

- The current evaluation of the threat;
- The nature of the material and its relative attractiveness to an adversary;
- The potential consequences associated with the *unauthorized removal* of nuclear material; and
- The potential consequences of *sabotage* against nuclear facilities or nuclear material.

A Design Basis Threat (DBT), describing the attributes and characteristics of potential insider and/or external adversaries, who might attempt *unauthorized removal* of nuclear material or *sabotage* should be used in planning and evaluating physical protection systems. Appropriate physical protection must be provided for the whole lifetime of a nuclear facility and the physical protection system should be flexible enough to allow adjustments to accommodate, on a contingency basis, threats which may exceed the DBT.

The concept of physical protection to protect a facility against *sabotage* requires a designed mixture of hardware (security devices), procedures (including the organization of *guards* and the performance of their duties) and facility design (including layout). When considering the measures required for the physical protection of nuclear material against *unauthorized removal* or *sabotage* factors such as the self-protecting nature of the material or the containment measures used for safety reasons should be taken into account.

The efficiency of the relevant functions of physical protection systems:

- Detection;
- Delay;
- Response; and
- Mitigation.

can be significantly improved by taking into account the physical protection needs in an early stage of facility design. Safety features such as redundancy or diversification in technology of relevant systems; layout criteria such as physical or geographical separation or segregation of systems; and the design of buildings against external events are introduced at the design phase of the facility. These provisions have the potential to improve physical protection of a nuclear facility by requiring more preparation, more means and more time to commit a malevolent action.

2.3. Energy system expectations for nuclear energy in the 21st century

In 1996 the Inter-governmental Panel on Climate Change (IPCC) commissioned a Special Report on Emission Scenarios (SRES) [2-11] to replace long-term reference emission scenarios first formulated in 1992. The 1992 scenarios had been developed to provide a common international basis for researchers and policy makers analyzing potential climate change impacts and mitigation options. By 1996, the IPCC believed an update was necessary to incorporate new data on energy resources, energy production and conversion technologies throughout the energy system as well as advances in climate modelling and related sciences. The SRES presents 40 reference scenarios, grouped according to four storyline families, extending to 2100.

Global primary energy use in the SRES scenarios grows between 1.7 and 3.7-fold between 2000 and 2050, with a median increase by a factor of 2.5 (Figure 2.1). Electricity demand grows almost 8-fold in the high economic growth scenarios and more than doubles in the more conservational scenarios at the low end of the range. The median increase is by a factor of 4.7.

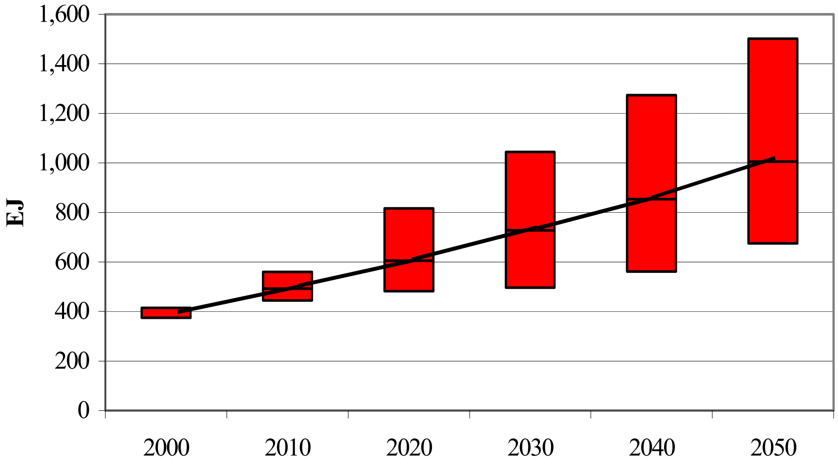


Figure 2.1. Range of future primary energy demand in SRES scenarios, 2000–2050. Solid line represents median. Source: Ref. [2-11]

The scenarios include substantial improvements in final energy intensities[6] of between 1% and 2.5% per year, with the higher improvement rates leading to lower total energy requirements. Given that improvements during the 20th century averaged about 1% per year, the scenarios thus assume that future potentials for further efficiency improvements continue to be exploited at a generally accelerating pace.

Most of the scenarios also include substantial increases in the use of nuclear power (Figure 2-2). Thirty-five of the 40 scenarios report results explicitly for nuclear power, not just “non-carbon technology,” and the 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)). These projected growth levels would require added global nuclear power capacity of 50–150 GW(e) per year from 2020–2050, even without any policies to reduce GHG emissions. They could be

---

[6] Final energy intensity is defined as the ratio of the sum of energy delivered to the end-user over gross domestic product (GDP) and serves as a proxy for energy efficiency improvements at the level of end-use, for structural economic change and for behavioural change. Low energy intensities usually result from a large share of electricity in the final energy mix.

higher if nuclear power were used to generate more than just electricity (i.e. in desalination and the production of chemical fuels).

The SRES also concludes that the future will most likely not be determined by one or more sources of energy running out. Even the steadily increasing use of fossil fuels, which now supply 87% of the world's primary energy use and 63% of electricity use, is unlikely to exhaust estimated resources.

Fossil occurrences are generally agreed to be plentiful, especially if we look beyond conventional reserves and take into account continuing technological progress in exploration and production. The same is true of nuclear resources.

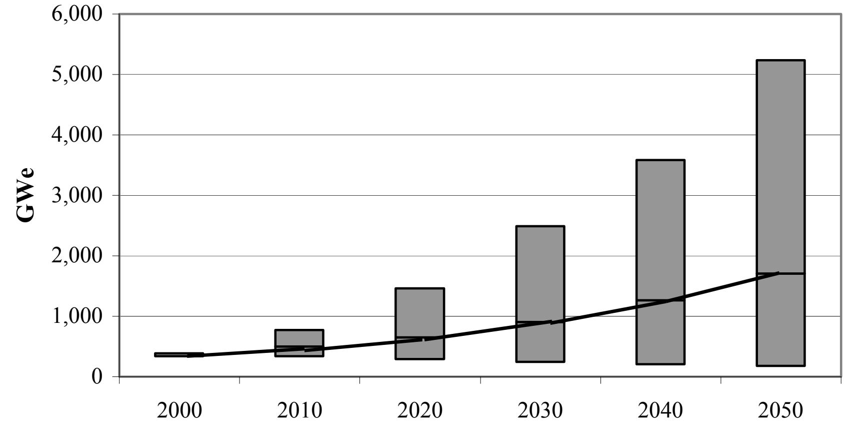


Figure 2.2. Range of nuclear power in SRES scenarios, 2000-2050. Solid line represents median. Source: Ref. [2-11]

None of the 40 scenarios includes policies designed to avoid or mitigate climate change. They are intended as reference scenarios, to which analysts can subsequently add their own proposed climate change policies if they wish. Or they can be used simply to study potential impacts caused by unrestricted greenhouse gas (GHG) emissions.

2.4. Concluding remarks

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. With the use of advanced fuel cycles and the deployment of breeder reactors, uranium and thorium represent virtually in-exhaustible energy resources.

Thus, nuclear energy can play an important role in meeting the expanding world energy demand, consistent with the principle of sustainable development, i.e. meeting the needs current generations without compromising the ability of future generations to meet their needs. 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.

The following sections set out Basic Principles, User Requirements, and Criteria that need to be fulfilled by Innovative Energy Systems to meet these challenges. If successfully developed, nuclear energy could assume a substantially greater role in meeting the demand for energy than is reflected in the Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change.

References to Chapter 2

[2-1] MINISTRY OF THE RUSSIAN FEDERATION FOR ATOMIC ENERGY, White Book of Nuclear Power, Moscow (2001).

[2-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology Review 2002, IAEA, Vienna (2002).

[2-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal of Radioactive Waste Requirements, Safety Standards Series No. WS-R-1, IAEA, Vienna (1999).

[2-4] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes, Safety Series No. 99, IAEA, Vienna, (1989). (currently being updated as Geological Disposal of Radioactive Waste", Safety Standards Series No. DS154).

[2-5] INTERNATIONAL ATOMIC ENERGY AGENCY, The Structure And Content of Agreements Between The Agency And States Required In Connection With The Treaty On The Non-Proliferation Of Nuclear Weapons, INFCIRC/153 (Corrected), IAEA, Vienna (1972).

[2-6] INTERNATIONAL ATOMIC ENERGY AGENCY, Model Protocol Additional To The Agreement(s) Between State(s) And The International Atomic Energy Agency For The Application Of Safeguards, INFCIRC/540 (Corrected), IAEA, Vienna (1997).

[2-7] INTERNATIONAL ATOMIC ENERGY AGENCY, The Agency's Safeguards System, INFCIRC/66/Rev.2, IAEA, Vienna (1965 as provisionally extended in 1966 and 1968).

[2-8] INTERNATIONAL ATOMIC ENERGY AGENCY, The Physical Protection of Nuclear Materials and Nuclear Facilities, INFCIRC/225/Rev4 (Corrected), IAEA, Vienna (1999).

[2-9] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance and consideration for the implementation of INFCIRC/225/Rev.4, The Physical Protection of Nuclear Material and Nuclear Facilities, IAEA-TECDOC-967 (Rev.1) Vienna (2000).

[2-10] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook on the Physical Protection of Nuclear Materials and Nuclear Facilities, IAEA-TECDOC-1276, Vienna (2002).

[2-11] INTERNATIONAL PANEL ON CLIMATE CHANGE, Special Report on Emission Scenarios, A Special Report of Working Group III, Cambridge University Press, Cambridge (2000), (<http://www.grida.no/climate/ipcc/emission/index.htm>).

CHAPTER 3
DEFINITIONS OF SELECTED TERMS WITHIN INPRO

Because of the broad scope of the INPRO project and associated documents – economics, environment, safety, waste management, proliferation resistance, and cross cutting issues – a common definition of important terms used in this report is necessary. Documents of interest to INPRO often use different terminology, even when discussing topics of a very general nature. For example, reference can be made to goals, objectives, principles, fundamentals, rules, etc. using different orders of precedence. Therefore, we describe below the more important terms used throughout this report and their relationship.

A **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. Within INPRO all types of reactors (e.g., cooled by light and heavy water, gas, liquid metal and molten salt, of different sizes of thermal power and use, such as for production of electricity, of process and district heat, and of freshwater, and for partitioning and transmutation of fission products) and associated fuel cycles (e.g., U, U–Pu, Th, U–Pu–Th cycle) should be considered. All phases in the life cycle of such facilities are included, such as site acquisition, design, construction, equipment manufacture and installation, commissioning, operation, decommissioning and site release/closure. Institutional measures consist of agreements, treaties national and international legal frameworks and conventions (such as the NPT, the International Nuclear Safety Convention, IAEA Safeguards Agreements) and the national and international infrastructure needed to operate a nuclear program. An example for such a Nuclear Energy System could be a combination of gas cooled thermal reactors and metal cooled fast reactors, a closed fuel cycle based on Plutonium/Uranium, reprocessing facilities but not enrichment, centralized fuel production, and waste treatment facilities.

Innovative Nuclear Energy Systems (INS) refer 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 [3-1] 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 [3-1] is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. These systems comprise not only electricity generating plants, but include also plants (of various size and capacity) for other applications, such as high-temperature heat production, district heating and sea water desalination, to be deployed in developed regions as well as in developing countries and countries in transition. See also Refs [3-2] to [3-7].

Within INPRO the demands on Innovative Designs of a Nuclear Energy System are structured in a hierarchical order (see Figure 3.1).

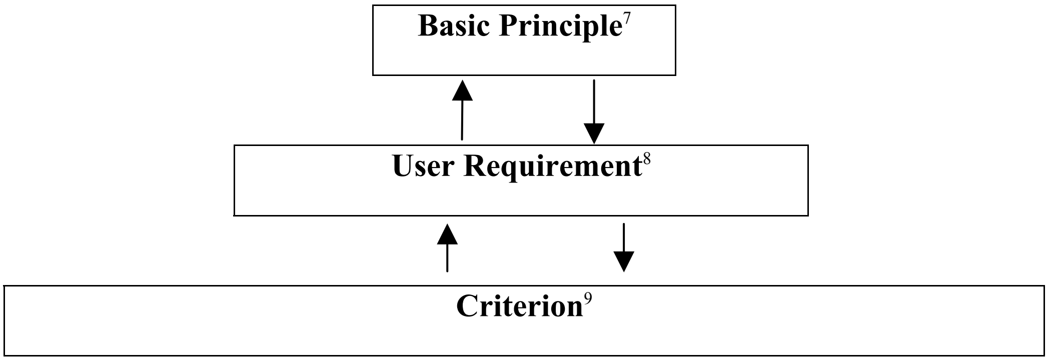


Figure 3.1. INPRO Hierarchy of demands on Innovative Designs of Nuclear Energy Systems.

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 Innovative Design (or design feature) of a Nuclear Energy System. All Basic Principles shall be taken into account in all areas considered within INPRO (economics, environment, safety, waste management, and proliferation resistance). An example of a Basic Principle, taken from the INPRO area of safety, is that an *Innovative Design shall incorporate enhanced defence-in-depth as a part of its fundamental safety approach*. (It should be noted that in some topic areas – primarily safety – even more general guidance compared with a Basic Principle is given in a General Objective. These General Objectives reflect a worldwide consensus and are valid for Innovative Designs as well as for existing designs.)

The second level in the INPRO hierarchy is called a **User Requirement (UR)**. URs are the conditions that must be met to achieve Users' acceptance of a given Innovative Nuclear Energy System. A User is an entity that has a stake or interest in potential applications of nuclear technologies. Users, in the context of INPRO, encompass a broad range of groups including:

- Representatives of investors, designers, energy commissions, power generators and utilities;
- Involved regulatory bodies, state local organizations and authorities, national governments, legislative bodies, stakeholders including non-governmental organizations (NGO), and decision makers;
- Interested media, communication organizations, the end users of energy (public, industry, etc.) and parties to the siting and licensing process; and
- Informed international organizations (e.g., IAEA, IEA, OECD, NEA, etc.).

The URs set out measures to be taken to ensure fulfilment of the Basic Principle(s) to which they relate. In the topic areas considered within INPRO, different types and categories of User Requirements can be distinguished. Some User Requirements are applicable to the total

---

[7] Corresponds to the term Goal in Generation IV International Forum (GIF).

[8] Corresponds to the term Criterion in GIF.

[9] Corresponds to the term Metrics in GIF.

Nuclear Energy System, some are valid only for specific components (such as the reactor) or for specific nuclear technologies (e.g., light water reactors), some relate to the functionality of a system or component, and some set out measures for implementation or methods of analyses. An example for a UR in the area of nuclear safety is the functional requirement, that an *Innovative design of a nuclear reactor shall not need evacuation measures outside the plant site.*

Finally, a **Criterion** (or more than one) is 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.). An example of a Criterion in the area of safety (related to the User Requirement in the preceding paragraph) could be the following: *The probability of a large release of radioactive materials to the environment should be less than* 10^{-6} *per year*. In this case the Indicator is the probability for a large release and the acceptance limit is the given value of 10^{-6} per year.

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); and
- The fulfilment of a User Requirement for an Innovative Design is confirmed by the Indicator(s) complying with the Acceptance Limit(s) of the corresponding Criterion (Criteria).

In the following sections the Basic Principles, User Requirements, and Criteria for Innovative Nuclear Systems are set out for the selected INPRO areas, namely, Economy, Environment, Safety and Proliferation Resistance. For the Crosscutting Issues it has been decided to define recommendations instead of requirements. The methodology for assessment of a Nuclear Energy System using the structure defined above is described in Chapter 5.

References to Chapter 3

[3-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Terms for Describing New, Advanced Nuclear Power Plants, IAEA-TECDOC-936, Vienna (1997).

[3-2] INTERNATIONAL ATOMIC ENERGY AGENCY Design Concepts of Nuclear Desalination Plants, IAEA-TECDOC-1326, Vienna (2002).

[3-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Heavy Water Reactors – Status and Projected Development, Technical Reports Series No. 407, IAEA, Vienna (2002).

[3-4] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, WORLD NUCLEAR ASSOCIATION, Small and Medium Sized Reactors: Status and Prospects, Proceedings of an International Seminar held in Cairo on 27-31 May 2001, C&S Papers Series No. 14/P, IAEA, Vienna (2002).

[3-5] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Related Design and Economic Aspects of HTGRs, IAEA-TECDOC-1210, Vienna (2001).

[3-6] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Liquid Metal Cooled Fast Reactor Technology, IAEA-TECDOC-1083, Vienna (1999).

[3-7] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Advanced Light Water Cooled Reactor Designs – 1996, IAEA-TECDOC-968, Vienna (1997).

CHAPTER 4
BASIC PRINCIPLES, USER REQUIREMENTS AND CRITERIA FOR INNOVATIVE NUCLEAR REACTORS AND FUEL CYCLES

4.1. Economics

4.1.1. Energy demand and the special report on emission scenarios (SRES)

As set out in Chapter 2, scenarios for future energy needs have been developed by the IPCC in a Special Report on Emissions Scenarios (SRES) [4.1-1]. The SRES scenarios show a wide range of possible energy demand reflecting uncertainties in the future, but none-the-less demonstrate that there will be a requirement for substantial increases in energy supply over the next fifty years, and, for almost all scenarios, the demand is expected to continue to increase beyond 2050. Further, electricity and, in many cases, hydrogen are expected to become increasingly important as energy currencies in the future.

To concisely reflect the wide range of scenarios in the published literature, SRES utilized four narrative storylines, each representing different demographic, social, economic, technological, and environmental developments. For each storyline, several different quantifications, or scenarios, were developed by six different international modelling teams. The four storylines are labelled A1, A2, B1, and B2. While the scenarios do not include policies designed to avoid or mitigate climate change, it should be noted that two of the four scenarios described below (A1T and B1) lead to atmospheric carbon concentrations consistent with current interpretations of the United Nations Framework Convention on Climate Change (UNFCCC) objectives. Thus, we consider the four scenarios discussed below to cover possible futures both with and without green house gas (GHG) constraints.

As shown in Figure 4.1.1, economic objectives dominate in the “A” storylines at the top of the figure while environmental objectives dominate in the “B” storylines. The “1” storylines on the left incorporate strong globalization trends and much greater international integration, while the “2” storylines on the right are better characterized by regionalism rather than globalization.

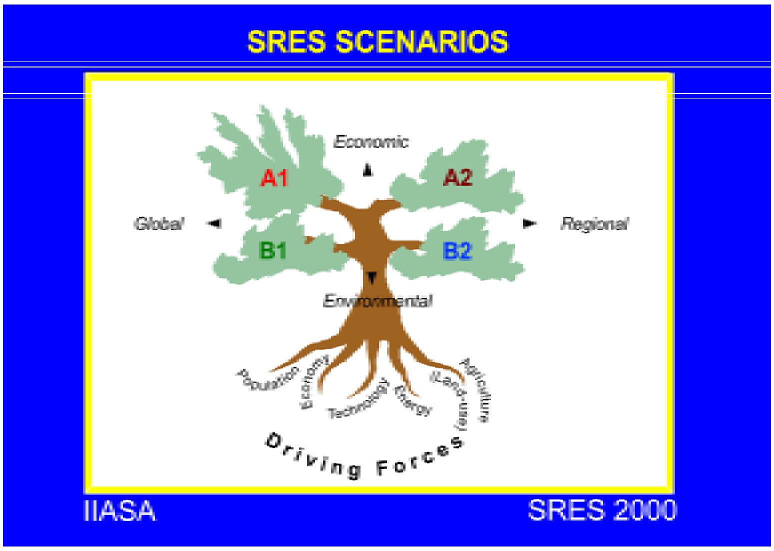


Figure 4.1.1. Schematic illustration of the four SRES storyline families [4.1-1].

The storylines in Figure 4.1.1 can be summarized as follows[10]:

- 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 changes 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 toward a service and information economy, with reductions in material intensity, and the introduction of clean[11] and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental challenges, including improved equity, but without additional climate initiatives; and

- 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.

The 40 scenarios in the full SRES report cover many variations within each storyline. However, the scenarios do not present the underlying energy system structures in enough detail for specific energy technology and infrastructure analyses. To clarify the range of possible nuclear energy technology requirements by mid-century requires a clear understanding and delineation of:

1) The overall energy system implied by a scenario; and
2) A more specific nuclear "translation" of each focused on scenario features particularly relevant to nuclear energy.

Langlois *et al.* [4.1-2] analyzed, for the A2, B1 and B2 storylines, a single scenario representative of central tendencies within the scenario family. For the A1 storyline, they analyzed a variation labelled the A1T Scenario[12].

---

[10] The summaries below are almost verbatim from the SRES report [4.1-1].

[11] Clean and resource efficient technologies include but are not limited to renewable technologies. They may also include fossil technologies with high efficiency and low levels of pollutant emissions, such as SOx or NOx. In addition, also hydrogen technologies are definitely clean and resource efficient at the point of use, but do not belong to the group of renewable technologies (particularly, if the hydrogen is produced from fossil fuels).

[12] The A1T scenario is a variation of the A1 scenario with a strong emphasis on advanced, efficient and clean energy technologies and rapid change toward post-fossil fuel alternatives. A1T has the lowest carbon emissions of the A1 scenarios. It was chosen principally because it is consistent with stabilizing the atmospheric carbon concentration at a level (560 ppmv), which is potentially consistent with the objectives of the UNFCCC, and we wanted to include at least one scenario other than the very green B1 Scenario that would meet UNFCCC objectives. The A1T Scenario also illustrates that decarbonization is possible in a world with very rapid economic and energy demand growth. The structure of the energy system differs considerably from so-called "conventional" fossil-intensive future worlds, and makes possible an exploration of the potential role of nuclear technologies in a very challenging and dynamic technology environment, characterized by rapid diffusion of new and advanced technologies.

For these scenarios primary energy use increases over the next century, as does electricity production. As well, the share of electricity in the overall energy use also increases.

4.1.1.1. Impact of various SRES scenarios on nuclear power development

The impacts of the four selected scenarios on nuclear power development are described briefly below (see also Figure 4.1.2).

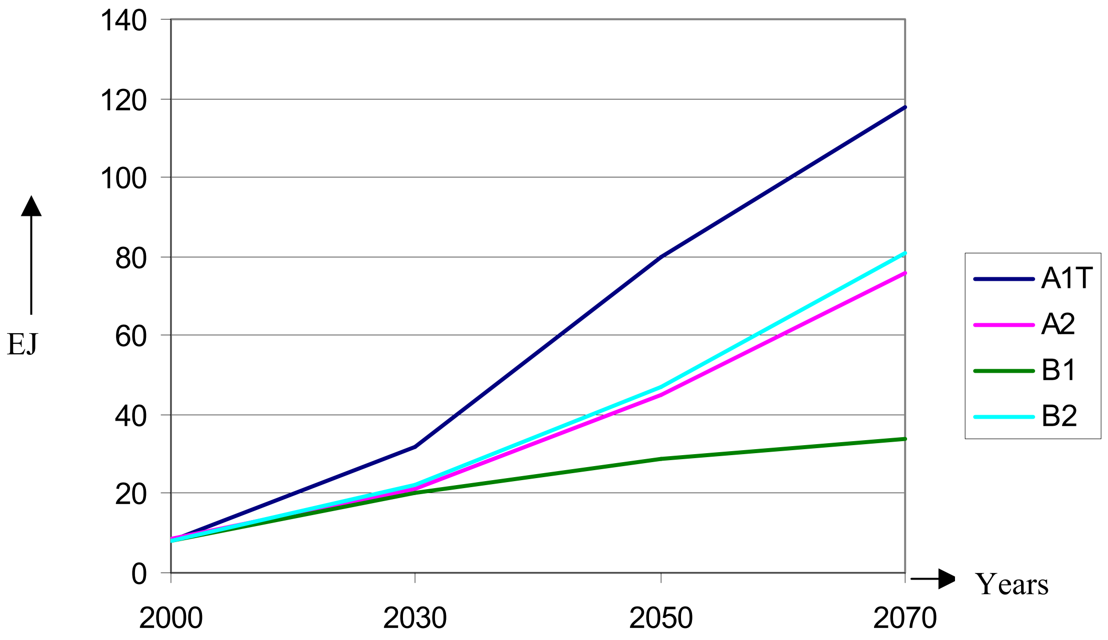


Figure 4.1.2. Nuclear electricity production (EJ) for the four selected scenarios.

A1T Scenario: The principal product market for nuclear is electricity with a significant market also in hydrogen, especially after 2030. The OECD-90[13] initially dominates hydrogen capacity growth. It shifts to Asia[14] and ROW[15] around 2050. Through 2030 electricity capacity additions are greatest in Asia, with ROW and OECD-90 tied for second. After 2030 principal growth is shared equally between ROW and Asia. Initial competition for new electricity capacity is initially quite balanced between coal, gas, nuclear, and solar. Coal looses market share around 2020 and gas around 2040, leaving the competition to nuclear and solar. In REF[16] and OECD-90, 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.

---

[13] The OECD-90 region includes all countries belonging to the OECD as of 1990 and corresponds to the Annex II countries in the UNFCCC.

[14] The Asia region stands for all developing (non-Annex I) countries in Asia.

[15] The ROW region stands for the rest of the world (beside OECD-90, Asia, and REF) and includes all developing (non-Annex I) countries in Africa, Latin America, and the Middle East.

[16] The REF region comprises those 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.

A2 Scenario: The product market for nuclear is exclusively electricity. There is no hydrogen production from NPPs. Capacity additions are principally in the OECD-90 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. Through 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-90 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-90, while solar is assumed to fare much better in Asia after 2030.

B1 Scenario: B1 is distinctive in that global and regional energy use (primary, final and electricity) peak around 2060-2080 and then decline. The distribution of nuclear power is similar to the A1T Scenario, but the shift from the OECD-90 to developing region markets is much faster. Principal product markets for nuclear are electricity and, especially after 2030, hydrogen. For both electricity and hydrogen, capacity additions are greatest in ROW, then Asia, then OECD-90, and, well behind, REF. Nuclear's principal competition for new electricity capacity is solar and, until 2040, gas. 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.

B2 Scenario: Nuclear power varies regionally, and by 2050 it is highest in Asia. During the 2040-50 period the Asia and ROW regions, i.e. developing countries, experience the greatest increase in nuclear additions effectively shifting the nuclear energy markets from the developed countries to principally the leading emerging economies among developing countries. Electricity remains the primary product of nuclear power plants.

4.1.1.2. Estimating the potential of nuclear markets

In reporting nuclear energy developments in the selected scenarios it is important for INPRO that these scenarios not be viewed as tight constraints, but as indications of opportunities. The 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 scenarios.

McDonald *et al.* [4.1-3] analyzed the four scenarios to estimate what additional potential exists for nuclear energy under a set of aggressive but plausible assumptions. The potential of nuclear technologies to gain additional shares differs considerably across the four selected scenarios because they represent future worlds of alternative market conditions and technology environments. First, this is due to the variation of the scenarios' socio-economic assumptions, which result in considerably different energy demand projections. Second, the scenarios differ also with respect to technology assumptions, which drive the evolution of the energy system in alternative directions. By analyzing the scenarios, they estimated key markets for additional nuclear shares compatible with the given path-dependent development in each of the four SRES worlds.

The results for the A1T scenario are illustrated in Figure 4.1.3.

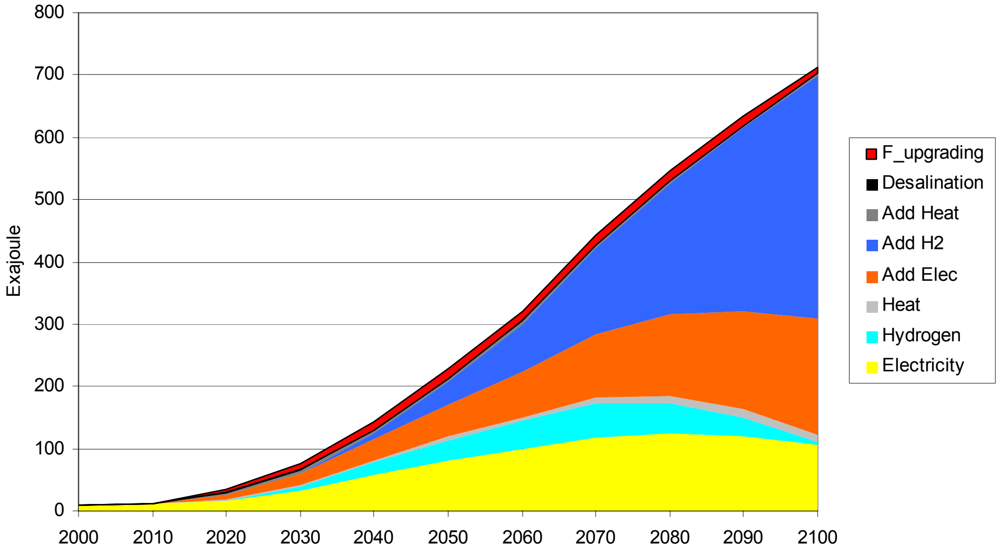


Figure 4.1.3. Potential global market for nuclear electricity, hydrogen, heat, desalination and fossil fuel upgrading for the A1T Scenario assuming aggressive but plausible nuclear improvements.

Figure 4.1.3 shows, first, the SRES projections for nuclear generated electricity[17], hydrogen, and heat. Nuclear electricity is the yellow area on the bottom, nuclear hydrogen is the light blue area above that, and nuclear heat (other than for desalination), is the thin sliver of light grey above that. Together these values correspond to the total nuclear energy production for the A1T Scenario and show a rise and fall in nuclear production with a peak around 2070–2080. The orange area in Figure 4.1.3 is additional nuclear generated electricity based on the assumption that improvements in the economics of nuclear electricity generation enable it to win market share from its competitors. The large dark blue area is additional nuclear generated hydrogen based on the parallel assumption that improvements in nuclear hydrogen generation are good enough for nuclear energy to win a share of the solar hydrogen market. The contributions of the additional nuclear generated district heat market and nuclear desalination are too small in the A1T Scenario to show up in the Figure. The red strip on top is the potential market for nuclear heat for upgrading unconventional oil resources, for coal gasification and liquefaction, and for synfuel production from coal.

Overall for the four SRES scenarios the main markets for the expansion of nuclear capacities are electricity and heat generation, and hydrogen supply. The scenario specific characteristics for possible additional nuclear shares beyond the level depicted by each of the four SRES scenarios are summarized below.

---

[17] Nuclear energy's share of global primary energy use depends on the convention used to convert nuclear electricity into primary energy. The convention used in IAEA projections assumes an effective nuclear efficiency of 37%, such that 3.6 terajoules (TJ) of nuclear electricity (equal to 1 GW(e)·h) correspond to 9.7 TJ of primary energy. Using this convention, the nuclear share of global primary energy use in 2001 was about 6%. In contrast, SRES converts nuclear electricity to primary energy on a one-to-one basis. 3.6 TJ of nuclear electricity correspond to 3.6 TJ of primary energy. Using this convention, the nuclear share of global primary energy use in 2001 was closer to 2%. For comparison, the nuclear shares of primary energy use in the "aggressive nuclear" variant of the SRES A1T Scenario shown in Figure 4.1.3 are, using the SRES convention, 18% in 2050 and 35% in 2100. Using the IAEA convention, they are 39% in 2050 and 62% in 2100.

Scenario A1T: The A1T Scenario depicts a world of high economic growth and rapid increase of energy demand. The comparatively fast turnover of capital promotes the expansion of nuclear. In the original SRES A1T Scenario nuclear contributes more than 100 EJ to global hydrogen and electricity production in 2050. Based on the assumptions made by McDonald et al. [4.1-3], nuclear may increase its contribution by an additional 90 EJ in 2050. In the very long term, the energy supply of the A1T Scenario shifts from fossil-based energy production toward renewable sources of hydrogen. The additional market potential for nuclear is vast, and could increase to 400 EJ of hydrogen and 200 EJ of electricity in 2100. Nuclear energy's biggest competitor is solar-based hydrogen production. Hence, nuclear strategies that focus on its potential to take an early share of the hydrogen sector seem to be most promising. The potential additional market for nuclear heat, either for district heating or upgrading fossil fuels, is small. There is very little centralized district heat in the A1T Scenario from fossil sources that nuclear heat could displace. There is also very little use of dirty unconventional fossil fuels and thus little potential demand for nuclear heat for fossil fuel upgrading.

Scenario A2: The A2 Scenario is characterized by heavy reliance on coal and relatively modest assumptions for economic growth. The scenario illustrates the long-term implications of quickly "running out of conventional oil and gas" combined with slow progress in developing alternatives. In the original SRES A2 Scenario nuclear technologies are predominantly used for power generation, increasing their contribution from 45 EJ in 2050 to 130 EJ in 2100. Clearly, in this scenario the main competitors for nuclear are coal technologies. In the electricity sector, nuclear could gain additional market shares of about 30 EJ in 2050 and up to 90 EJ in 2100. In the non-electric sectors, nuclear technologies could supply process heat for coal-based gasification and liquefaction processes. Using the assumptions of McDonald *et al.* [4-1.3], nuclear energy could increase its contribution to heat supplies in the A2 Scenario by more than a factor of six in 2100, which would correspond to additional heat generation of about 110 EJ.

Scenario B1: The B1 world describes a convergent world characterized by "reductions in material intensity, and the introduction of clean and resource-efficient technologies" [4.1-1]. The slow growth of energy demand and the focus on decentralized energy supply strategies, hinder the diffusion of nuclear technologies. This results in the smallest contributions of nuclear energy across all four SRES scenarios (30 EJ in 2050 and 40 EJ in 2100). In the long run the energy system is dominated by hydrogen and electricity from renewables and natural gas. The main competitors for nuclear are solar technologies in the hydrogen sector and natural gas and renewable power generation in the electricity sector. Strategies to promote nuclear technologies could increase the contribution from nuclear energy by more than a factor of two. By 2100, this would correspond to additional gains for nuclear energy of about 30 EJ of hydrogen and 50 EJ of electricity. The potential additional market for nuclear heat, either for district heating or upgrading fossil fuels, is small. There is very little centralized district heat in the B1 Scenario from fossil sources that nuclear heat could displace. There is also very little use of dirty unconventional fossil fuels and thus little potential demand for nuclear heat for fossil fuel upgrading.

Scenario B2: The B2 Scenario describes a world based upon "dynamics as usual" assumptions with intermediate economic growth. Due to the focus on local rather than global solutions, the energy system in the B2 Scenario develops very heterogeneously. Hence, major competitors for nuclear energy differ from region to region, depending on regional circumstances such as resource and technology availability. In the original SRES B2 Scenario nuclear technologies are predominantly used for power generation, and increase their contribution from 45 EJ in 2050 to about 140 EJ in 2100. Based on their assumptions, McDonald et al. [4.1-3] estimate that electricity generation from nuclear energy could be expanded by another 30 EJ in 2050 and 70 EJ in 2100 respectively. These additional shares for nuclear would result in slower market penetration for coal in Asia; for natural gas and biomass technologies in the developing world; and, to a lesser extent, for solar power generation globally. In addition to electricity, nuclear technologies could also supply considerable amounts of process heat for the production of synthetic fuels and upgrading of fossil fuels (10 EJ in 2050 and 40 EJ in 2100).

4.1.2. Learning, technology development and the SRES scenarios

4.1.2.1. Introduction

Economic competitiveness is a constantly moving target since feedback from experience leads to innovation and resulting improvements in technology. The concept of technological learning was first introduced over 60 years ago by Wright [4.1-4]. Simply put, a technology's performance improves as experience with the technology accumulates. The concept can be used with a variety of different indicators of technological performance and experience. By way of example, we could use specific capital cost as the performance indicator and total cumulative installed capacity as the experience indicator. In this case, technological learning is defined by the following power function.

$$\text{Cost} = A^* \text{Ccap}^b \qquad \text{(Eq. 1)}$$

Where

Cost	are the specific capital costs (e.g., \$/kW(e)),
A	are the specific capital costs at a total cumulative capacity of 1,
Ccap	is the total cumulative installed capacity (e.g., GW(e)), and
b	is the learning elasticity (a constant).

From this definition it follows that a doubling of total cumulative capacity reduces specific costs by a factor of 2^b. In the usual case where b is negative, 2^b (labelled the *progress ratio,* pr) is between zero and one. The complement of the progress ratio (1–pr) is called the *learning rate* (lr)[18]. A learning elasticity of –0.32, for example, yields a progress rate of 0.80 and a learning rate of 20 percent. This means that the specific capital cost of newly installed capacity decreases by 20 percent for each doubling of total installed capacity. On a double-logarithmic scale, the decrease in cost appears as a straight line.

Empirically derived learning rates are presented in Figure 4.1.4. The right panel shows Dutton and Thomas' 1984 compilation of learning rates for over 100 different production programs in individual manufacturing firms [4.1-5]. The left panel shows McDonald and Schrattenholzer's 2001 compilation of 26 estimated learning rates for various energy technologies [4.1-6]. The median value of 16-17% for energy technologies is not far below the 19-20% median for the manufacturing firms, and the ranges are comparable, from below zero (i.e., "forgetting rates") at one end to above 35% at the other end in both studies.

---

[18] For some data sets, estimating a learning curve leads to values of *b* equal to or greater than zero. Thus costs stagnate or *increase* with cumulative experience. In these cases, the terms "progress ratio" and "learning rate" are still used, although they are no longer as intuitively descriptive.

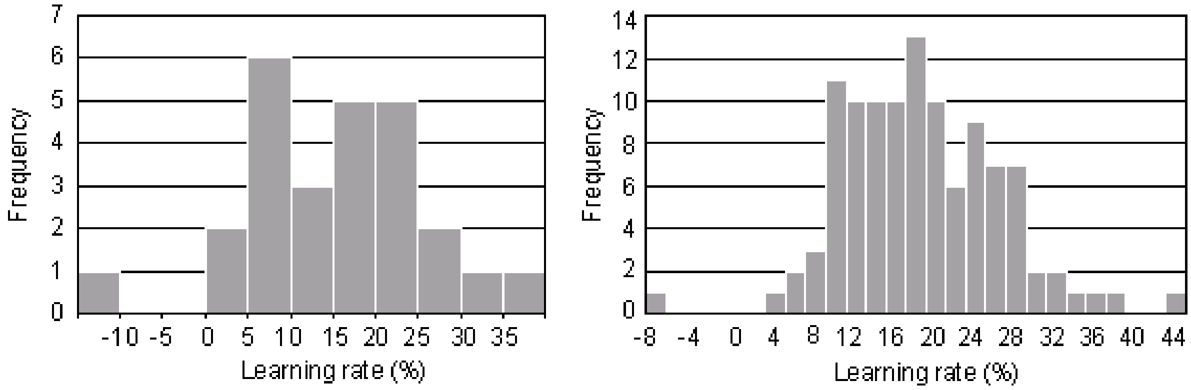


Figure 4.1.4. Distribution of learning rates observed for energy technologies (left panel, Ref. [4.1-6]) and for general industry (right panel, Ref. [4.1-5]).

From an analysis of the four SRES scenarios discussed above, namely the A1T, A2, B1, and B2 scenarios, it is possible to derive the learning rates implied by the cost data input to the version of IIASA's MESSAGE model[19] that was used to derive the total energy demand and the distribution of energy supply for the different scenarios in the SRES study. The cost data input for the SRES scenarios assume decreases in technological costs as a function of *time*, not as an explicit function of experience (cumulative capacity). Because, however, cumulative capacity increases with time in each scenario, a plot of a technology's cost as a function of its installed capacity in a given SRES scenario can be used to determine the learning rates implicit in the scenarios for the various energy technologies. The results of this exercise are presented in Table 4.1.1, which compares implicit learning rates for the four original SRES scenarios for the same power generation technologies.

Several observations are in order. The results in Table 4.1.1 generally show lower learning rates, for a given scenario, for established technologies and higher learning rates for new technologies. That is consistent with the concept of knowledge depreciation. Knowledge depreciation refers to the fact that experience gained ten years ago is not as valuable as experience gained yesterday. There is evidence that empirical learning curves tend asymptotically towards a constant cost as cumulative capacity increases [4.1-8, 4.1-9, and 4.1-10]. Grübler [4.1-9] suggests this reflects a technology's passage through different stages of its life cycle – specifically the learning rate is higher in a technology's initial R&D and

---

[19] MESSAGE is a large-scale dynamic systems-engineering optimization model that is used for medium- to long-term energy planning, energy policy analysis, and scenario development [4.1-7]. At the core of MESSAGE is a Reference Energy System (RES), which includes the full menu of primary energy options, final energy forms and conversion technologies. The RES includes fossil resources (such as coal, oil and gas), nuclear, and various renewable energy sources. Final energy is produced as liquid, solid and gaseous fuels, electricity, and district heat. Alcohols, hydrogen and other synthetic fuels are alternative options to currently established fuels. Energy demands are external to the model. They can be defined on the level of final or useful energy. In the latter case, demand distinguishes between thermal and specific (mostly electricity) uses in the industry and residential/commercial sectors, and between passenger and freight transport demands. MESSAGE results include optimal (i.e., least-cost) energy supply and utilization structures, resource extraction profiles, marginal cost and quantities of energy traded internationally, investment requirements in the energy sector, and pollutant emissions. Energy supply responds to relative energy prices in MESSAGE in the form of substitution effects guided by the overall optimization procedure. In its most common form MESSAGE includes separate variables for each of eleven world regions. These world regions are linked by international trade of primary and/or final energy. Typically, a world region includes approximately 150 technologies. In addition, the model includes variables describing energy conversion from resource extraction and imports up to final utilization in the end-use sectors. Altogether, the 11-region version of MESSAGE has approximately 35,000 variables and 50,000 constraints, depending on the number of new technologies included.

technical demonstration phase and lower in its later commercialization stage. McDonald and Schrattenholzer [4.1-10] propose an alternative explanation based on the work of Argote [4.1-11]. If experience depreciates – i.e., if knowledge gained from a capacity increase ten years ago is not as valuable as knowledge gained from a comparable capacity increase yesterday – a learning curve will begin to flatten if capacity ever grows less than exponentially and may even turn upwards if capacity growth is slow enough. Even if capacity growth remains exponential, knowledge depreciation will result in a lower, though constant, empirical learning rate than would have been the case without knowledge depreciation. The learning rates in the left panel of Figure 4.1.4 were all estimated using Equation 1, i.e., assuming no knowledge depreciation. A number of the low learning rates in that panel were estimated from data for coal, lignite, and hydropower plants covering periods when new capacity was not growing exponentially. Thus the low estimates for these technologies may in part be due to knowledge depreciation.

Table 4.1.1. Implicit learning rates for the principal power generation technologies in the A1T, A2, B1, and B2 Scenario

Technology description	Learning rates in the SRES scenarios			
	A1T	*A2*	*B1*	*B2*
Advanced coal power plants; e.g., integrated gasification combined-cycle (IGCC).	2%	2%	2%	1%
Gas combined-cycle power plant.	13%	3%	14%	12%
Biomass gasification power plant.	14%	6%	15%	5%
Conventional nuclear power plant, high costs, high performance.	5%	1%	4%	1%
Nuclear high temperature reactor, cogeneration of hydrogen and electricity.	4%	0%	3%	0%
Solar thermal power plant with storage, and solar thermal power plant for H_2 production.	10%	4%	9%	5%
Solar photovoltaic power plant (no storage).	15%	10%	13%	10%
Wind power plant.	14%	6%	10%	6%
Photovoltaic on site electricity production in the residential/commercial sector.	15%	10%	13%	10%
Photovoltaic on site electricity production in the industry sector.	15%	10%	13%	10%

Interestingly, although the general pattern of inferred learning rates in Table 4.1.1 is consistent with knowledge depreciation, the learning rates for renewable technologies may well be too high in later periods. The assumed cost improvement rates are too fast in later periods to be consistent with both the learning model of Equation 1 and the ever increasing increments that are needed to constitute "capacity doubling" as cumulative capacity grows. I.e. the decrease in cost as a function of installed capacity would be expected to tend asymptotically to some minimum value as has been discussed in a recent paper by Duffey [4.1-12].

Duffey has extended his work on the role of learning in error reduction in social, transportation and industrial processes [4.1-13] to economics. He argues that learning to reduce cost is directly dependent on market price differentials and target costs and that the rate of cost reduction is proportional to the excess price above the attainable minimum, leading to a learning function, which he calls the Marginal Minimum Cost Equation, with a finite final product cost. He has analyzed product cost data for a variety of technologies including photovoltaic cells, gas turbines, and ethanol production using his methodology and the results suggest that cost reductions for photovoltaics may already be flattening out.

4.1.2.2. Learning rates and nuclear cost improvements

The results presented in Section 4.1.1 showed that there is substantial potential for nuclear to displace other energy sources in the SRES scenarios. An analysis has been carried out of the impact of different assumed learning rates for nuclear technology on the contributions of nuclear power and nuclear-based hydrogen production in the SRES scenarios using a variation on the IIASA MESSAGE model, labelled MESSAGE-ETL, that incorporates technology cost decreases as a function of experience rather than time, for nuclear as well as for competing energy technologies such as solar and other renewable technologies and fossil energy technologies.

The results are summarized in Table 4.1.2. This shows, first, the implicit nuclear learning rates for the original four SRES scenarios as in Table 4.1.1. Second, Table 4.1.2 shows the higher nuclear learning rates necessary for MESSAGE-ETL to reproduce the faster and more extensive nuclear build-up trajectories corresponding to the four "aggressive nuclear improvement" scenarios described in Section 4.1.1.2.

Table 4.1.2. Learning rates as implied by the four selected SRES scenarios and as required to match the "aggressive nuclear improvement" variations on these scenarios

Scenario	Implicit learning rate in original SRES scenario	Learning rate to match "aggressive nuclear improvement" variant
A1T	4-5%	7%
A2	0–1%	6%
B1	3–4%	10%
B2	0–1%	8%

It should be noted that, because the development of MESSAGE-ETL and the scenario analysis proceeded in parallel, and because of different data availability for different scenarios, not all scenarios were analysed with the same version of MESSAGE-ETL. For the first scenario, A1T, an initial one-region version of MESSAGE-ETL was used. The B1 Scenario was then analysed using an 11-region version of the model. For the A2 and B2 Scenarios, a four-region version was used, as disaggregated data for these scenarios were readily available only for the four SRES regions – OECD-90, REF, Asia and ROW. One weakness of the one-region model used for the A1T Scenario is that all resources around the world are equally available to meet all consumer demands, no matter where they arise. Thus, when the A1T Scenario is re-analysed with a multi-region version on MESSAGE-ETL, and resources cannot flow instantly around the world, we expect that a higher nuclear learning rate than the 7% shown in Table 4.1.2 will be needed.

It must be emphasized that the absolute learning rate values shown in the second column of Table 4.1.2 should not be taken as numerical targets that will determine success or failure since these values depend on the learning rates implicitly assumed for competing technologies as set out in Table 4.1.1. Rather the important message is that for nuclear technology to remain competitive it must benefit sufficiently from learning to keep it competitive with competing energy technologies.

4.1.2.3. Converting learning rates to static cost targets

Given a specified learning rate and a trajectory for capacity expansion over time, it is straightforward to calculate the implied costs for each scenario as a function of time using Equation 1. Figure 4.1.5 shows the results for capital costs (overnight costs plus interest during construction, per kilowatt electric) in 2050 for all eight scenarios discussed above. The suffix "-N" identifies the aggressive nuclear variants of the four original SRES scenarios. The range in the year 2000 is also from the SRES scenarios. The bar labelled "NTR" shows the range of current costs presented in the IAEA's *Nuclear Technology Review 2002* [4.1-14] based on data from the European Commission and the OECD [4.1-15, 4.1-16].[20]

MESSAGE-ETL recognizes that in any given year, both the operating fleet of reactors, and any new reactors installed in that year, include a mix of technologies. The most expensive reactor among the new additions is probably cheaper than the most expensive reactor among the operating fleet, which is at least several decades old. The bars in Figure 4.1.5 show the range from the least expensive nuclear technology added in 2050 to the most expensive nuclear technology added in 2050, i.e., the range in which nuclear power plants are found by the model to be attractive investments.[21] In the A1T and B1 Scenarios (and in the base year 2000) the top of the bar corresponds to more complex high-temperature reactors capable of co-generating electricity and hydrogen. The bottom of each bar corresponds to simpler nuclear technologies generating only electricity.

---

[20] NTR cost estimates are inflated from assumed 1998 dollars to 2000 dollars (as used in the SRES report) using the GDP implicit price deflator from the U.S. Department of Commerce.

[21] The one exception is the bar for the B1-N Scenario. In 2050, the model is still "buying" the last few new units of an old $1600/kW(e) reactor technology. Because new additions of this old technology are phased out shortly thereafter, the top of the bar represents the next most expensive nuclear technology still being "bought" by the model as a better indicator of the upper bound for competitive costs in 2050.

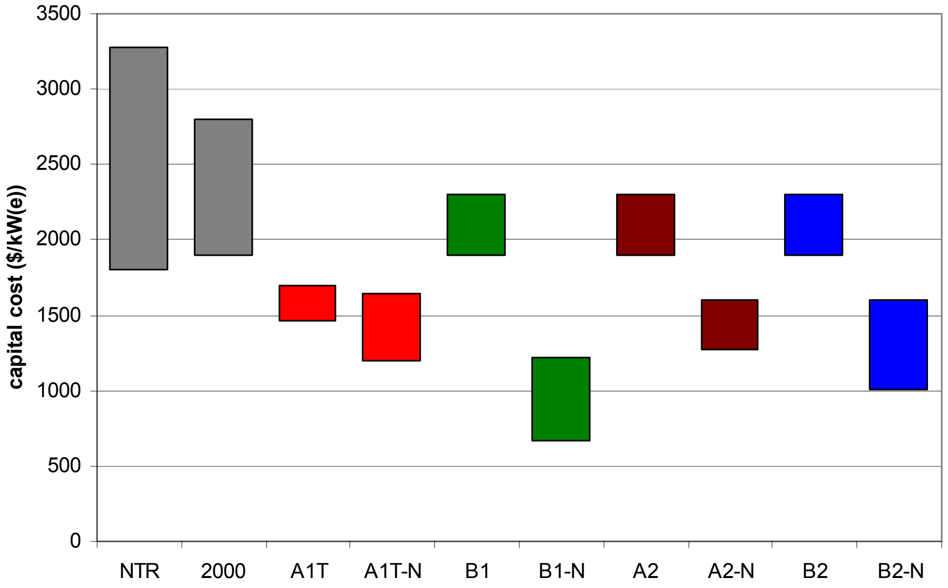


Figure 4.1.5. Ranges for specific capital costs in 2050 for nuclear power plants in eight scenarios.

Figure 4.1.6 presents comparable targets for the cost of nuclear electricity production in 2050, not including fuel costs. Note that the "NTR" production costs assume a 10% discount rate compared to the 5% used in SRES, and include fuel costs, unlike the SRES results. Both these factors would account from some of the difference between the NTR and SRES cost ranges in 2000.

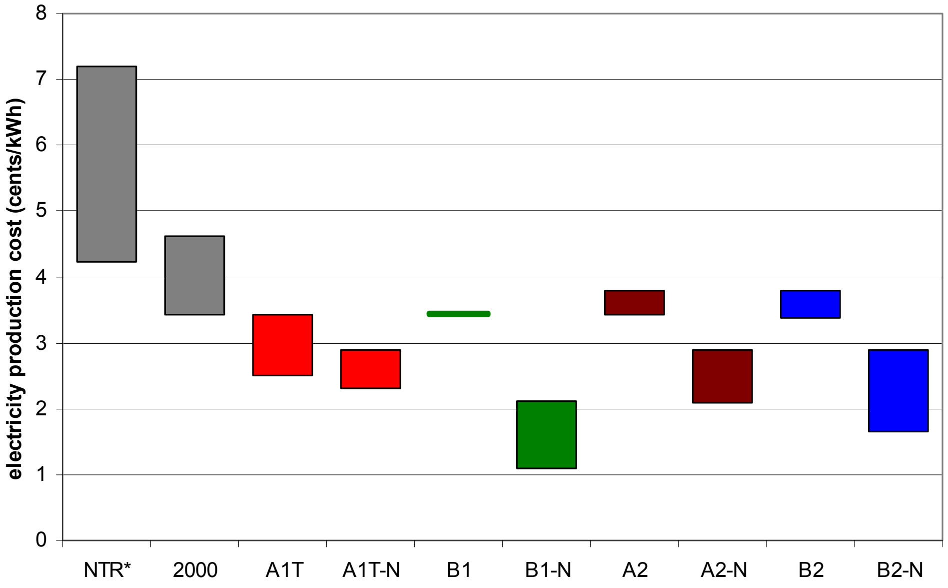


*Figure 4.1.6. Ranges for electricity production costs (exclusive of fuel costs) in 2050 for nuclear power plants in eight scenarios. (*The NTR bar includes fuel costs and is based on a 10% discount rate. The other bars do not include fuel costs and are based on a 5% discount rate.)*

4.1.2.4. Interpretation

Should RD&D strategists consider the results in Figures 4.1.5 and 4.1.6 as cost targets for competitive nuclear designs in 2050? Although these results are indeed the cost ranges in which the scenarios find nuclear technologies to be attractive investments, any application should take into account the following qualifications about the scenarios.

INPRO begins with scenarios because they are the best mechanism for systematically incorporating a host of uncertain factors when estimating the capital and operating cost levels likely to make an innovative nuclear reactor an attractive investment in 2050. Such factors include how much populations grow around the world; how much economies grow and change; how lifestyles evolve and how that is reflected in changing market demands and changing safety, environmental and non-proliferation constraints; how extensive various energy resources prove to be; how quickly alternative technologies advance; and how quickly ideas, money, people and technologies move around the world. Scenarios incorporate all these, and more, consistently and systematically.

We therefore chose the best pedigreed independent set of scenarios available, those in the IPCCs Special Report on Emissions Scenarios (SRES), and extracted the relevant capital and production costs for nuclear technologies that those scenarios consider attractive investments in 2050. Those costs are shown by the bars labelled A1T, B1, A2 and B2 in Figures 4.1.5 and 4.1.6. Throughout the analysis, we emphasized the concept of technological learning measured by learning rates in order to focus on the need for continuous learning and improvement if a future technology is to be consistently competitive.

The nuclear costs in the SRES scenarios for 2050 (the A1T, B1, A2 and B2 bars in Figures 4.1.5 and 4.1.6) are, however, not as low as was expected. Below are two possible explanations that users of this report might want to take into account in setting cost targets to guide their nuclear RD&D strategies.

First, the MESSAGE model optimizes total energy system costs through 2100 using a discount rate of 5%. The current front-loaded cost structure of nuclear technologies (high initial capital costs and low long term costs) is therefore less of a disadvantage in the scenarios than it would be for an investor in a liberalized energy market who faces higher financing charges than 5% and needs a rapid return on his investment. Thus MESSAGE is likely to still "buy" nuclear technologies with high capital costs even when a private investor in a liberalized market might not. We recognize that not all prospective investors will be private companies seeking quick returns in fully liberalized markets. Many are likely to be governments that can focus on longer term returns, and for whom low discount rates are appropriate. But if the objective is a design attractive to private investors in liberalized markets, the cost targets should probably be lower than those extracted directly from the SRES scenarios.

A second related consideration is that in MESSAGE, investments are essentially risk free and benefit from the model's "perfect foresight". Given the investment risks that exist in actual markets, both for private investors and governments, costs may need to be lower than shown in Figures 4.1.5 and 4.1.6 for nuclear technologies to still be attractive investments once investment risks are taken into account.

Although these comments are directed to the four original SRES scenarios, they also apply to the four aggressive nuclear variants. In addition, in the case of the aggressive nuclear variant of the A1T Scenario (i.e., A1T-N), as noted above, the costs in Figures 4.1.5 and 4.1.6 were calculated using an initial one-region version of MESSAGE-ETL. When the scenario is re-analysed with a multi-region version of MESSAGE-ETL, the result is likely to be a higher nuclear learning rate than the 7% shown in Table 4.1.2, and correspondingly lower costs.

4.1.3. Basic economic principles

As has been set out above, if nuclear technology is to compete successfully with alternate energy sources, it is necessary that the technology has the capacity to learn from experience. But, for such learning to take place, experience must be gained. I.e. there must be new installations of nuclear energy production systems and the total installed capacity must grow with time. Learning is coupled with experience and there is positive feedback between experience and learning – the greater the rate of learning the more competitive the technology and the faster its expansion and hence the greater the experience base leading to additional learning and so on. So, the starting point is convincing decision makers and stakeholders to install new capacity. While many factors enter into such decision-making, the key economic factor is cost competitiveness. This then leads to the following statement of the two economic basic principles that must be met:

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.***

This statement reflects the fact that, given options, customers will tend to choose the lowest cost option. But, choices of energy supply do not depend only on the up-front cost. Other factors associated with competing energy sources such as safety and environmental impacts, and socio-economic benefits, e.g., contributions to industrial development and security of energy supply, enter into the decision-making. Thus, costs or credits may be assigned to either the nuclear energy source or to the alternative source or both. But, if innovative nuclear energy systems cannot produce energy (or energy products) at a cost that is competitive with alternatives, taking into account associated benefits, the alternative technologies will in due course squeeze nuclear energy sources out of the market. Thus, experience will saturate, learning will stop and the technology will lose market share at a progressively faster rate.

Basic Principle 2: ***Innovative nuclear energy systems must represent an attractive investment compared with other major capital investments.***

To develop and deploy innovative energy systems requires investment and those making the investment must be convinced that their choice of investment is wise. The alternatives for investment may be other energy sources seeking investment for development and deployment or non-energy technology areas. So, INS must compete successfully for investment. In different markets and regions the source of investment may be different and different factors may assume more or less importance in determining attractiveness of investment as is discussed in more detail below.

4.1.4. Economic user requirements and criteria

4.1.4.1. Requirements related to principle 1

The user requirement and related criterion related to the first Basic Principle are set out in Table 4.1.3.

Table 4.1.3. User requirements and criteria related to Principle 1

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*		
Requirements	Criteria	
	Indicator	Acceptance Limit
1.1 *All life-cycle costs included in the energy system shall be accounted for and the cost of nuclear generated energy, C_N, shall be competitive with that of alternate energy sources, C_A.*	Cost of nuclear energy, C_N	$C_N < kC_A$

For INS to be competitive with alternative energy sources the net cost to the consumer, be it an industrial consumer, a small business, or an individual, must be comparable to or lower than the cost of alternate energy sources. In determining the cost of energy from INS and competing alternatives all relevant costs must be included. So,

User Requirement 1.1: *All life-cycle costs included in the energy system shall be accounted for, and the cost of nuclear generated energy shall be competitive with that of alternatives.*

The lifecycle cost of nuclear energy, $C_{N,}$ shall be competitive with the life cycle cost of the principle alternatives, C_A. In a given country/region many factors can enter into the decision-making regarding the choice(s) of energy supply. These include, for example, considerations of security of energy supply, long term stability in energy costs, diversity of energy supply technologies; the desire for industrial development and the role nuclear technology can play in such development; judgments about environmental impacts, either positive or negative, avoided emissions, safety, sustainability, waste management; public and hence political acceptance, etc. Such considerations may lead decision makers to accept a somewhat higher cost for one energy option compared with an alternative.

Thus, the related criterion, becomes

$C_N < kC_A$, where k is a factor that can be less than or greater than one in a given MS or region depending on whether or not nuclear costs are offset by credits relative to the alternative energy source or vice versa.

C_N and C_A should be calculated using a levelized discounted production cost model (See, e.g., Ref. [4.1-17]) taking into account all relevant cost determinants. Costs should be based on the costs for repeat units, rather than for a first of a kind unit. The model should be transparent and complete. Cost determinants include the following: specific capital costs for overnight construction, operating and maintenance costs, fuel costs, the cost of periodic upgrades expected over the anticipated plant lifetime, such as the replacement of I&C systems or the refurbishment of steam generators, capital discount rate, owner’s costs and in particular land use costs, the anticipated capacity factor, which takes into account among other things the availability factor and the load factor, insurance costs, the plant lifetime, net electrical output taking into account thermal efficiency, construction/project time, labour rates for engineering and construction, operating and contracted staff complements, amortization period, fuel burnup, decommissioning and waste management costs, interest during construction, credits/penalties applied, e.g., credits for avoided emissions or industrial benefits, profit/dividends, etc.

For an INS some of these costs, particularly at the conceptual design stage may have uncertain values, and hence may encompass or require ranges of estimates. Such a range and the relevant assumptions can be stated or assumed for any cost element provided it has some basis in accounting. The completeness and the ranges of the costing methodology may be regarded as a measure of the maturity of the INS design. As the INS proceeds through the stages of development (conceptual, feasibility, prototype, first of a kind) the cost estimates will be refined and the uncertainties reduced. But costing a competitive INS as it evolves is an important and necessary discipline.

Depending on the nature of the dominant competing energy technology(ies), locally, or nationally, at a given point in time and in a given region/country, the acceptance limit for a given indicator, say specific capital cost, may be different. Thus, in the near to intermediate term (say over the next 20 to 30 years) fossil-fired thermal plants, e.g., coal-fired or combined cycle gas turbines, are likely to be the prime competition with nuclear for electricity production. Thus, reductions in the specific capital costs of nuclear power plants while maintaining low fuel and O&M costs would improve the competitive position of INS. As well, waste management and decommissioning costs cannot contribute significantly to total unit energy costs.

In a number of the SRES scenarios, discussed briefly above, renewable energy sources such as photovoltaics and wind power represent the primary competition for nuclear energy. These technologies are characterized by low, if not 0, fuel costs and, if successfully developed, low maintenance costs. The main cost is the capital cost of construction and installation and the ‘cost’ of land use. The latter is sometimes treated as a ‘rent’ and hence becomes, in effect, analogous to a fuel cost. Alternatively, land use costs may be considered an owner’s cost. In some jurisdictions, land use can be an important factor and the much higher energy output of nuclear plants for a given plant footprint, MW(e)/hectare, is one of nuclear technology’s competitive advantages compared with renewables (see for example Ref. [4.1-18]). Another competitive advantage is the higher capacity factors expected from nuclear technologies compared with those from renewables. In recent years average availability factors >90% have been achieved. With INS even higher availability factors, ~95% should be achievable. To compete against renewables, the latter factors, taken together with capital costs, must outweigh any advantages that renewables might have in areas of fuel costs (not including any land use fees) and operating and maintenance costs.

While the end product of the INS is energy produced by a reactor, other components include the facilities for fuel production including reprocessing and waste management facilities and in particular the end-state waste facility(ies). If the total unit energy cost of nuclear energy is to be competitive, the cost of the fuel used in the energy production machine – the reactor – must remain low. Thus, the capital cost and the operating and maintenance costs of the nuclear fuel cycle facilities other than the reactor must be sufficiently small that the fuel costs to the reactor operator are competitive. Fuel cycle facilities also produce waste, which must be safely managed, including placing it in a safe end-state and, in due course, the facilities have to be decommissioned. The cost of all these activities and the associated waste management facilities must be such that the fuel costs remain low.

In short, the operator of a nuclear energy plant will act as a customer for the fuel cycle facilities and innovative fuel cycle facilities must be competitive with alternate fuel strategies, which may be coupled with alternative reactor designs.

But, overall, it is clear that, for INS, the capital costs, the operating and maintenance costs, the fuel costs, the waste management costs, and the decommissioning costs must individually and collectively be sufficiently low to make the total unit energy cost of the end product competitive. Thus from an economic perspective the INS need to decrease overnight construction costs, decrease construction times and hence interest during construction, decrease O&M costs, increase life cycle average availability, and extend plant lifetimes, all without compromising safety or environmental performance.

4.1.4.2. Requirements Related to Principle 2

The requirements related to the principle that nuclear energy systems represent an attractive investment opportunity and the associated criteria are set out in Table 4.1.4.

The first basic principle and user requirement related to competitiveness, discussed in Section 4.1.4.2, are also important to investor confidence, since investors must have confidence that the technology in which they are investing will compete successfully and so generate sufficient revenue to pay back their investment with an attractive rate of return. Thus, the cost competitiveness of innovative energy systems is an overarching requirement.

In addition, the total investment required, the rate of return on the investment and investor risk are also important factors. This leads to the four requirements set out in Table 4.1.4. These are discussed below.

Economic User Requirement 2.1: *The total investment required to design, construct, and commission innovative nuclear energy systems, including interest during construction, must be such that the necessary investment funds can be raised.*

The total investment depends on the overnight construction cost and interest during construction, while the latter depends on construction time and the time to commission. Thus, the direction to be taken for innovative energy systems is to reduce both construction costs and the time to construct and to commission. A universally applicable criterion for what constitutes an acceptable level of investment cannot be defined a priori since this will vary with time and region and will depend on many factors such as alternatives available, etc.

Investor risk comprises two factors – project delays and shortfalls in plant operation. The latter is discussed below. Here we note that the greatest impact of project delays arise during construction and commissioning. The time taken to construct new facilities and to bring them into operation (and so to start to generate revenue) should be as short as practicable. In assessing the time taken to design, construct and commission a new plant it needs to be recognized that front end design work, environmental assessment, and licensing applications, while potentially lengthy, represent a relatively small investment compared with the investment required to procure, construct, install, staff and commission new facilities. Commissioning comes at the end of the process when the majority of investment funds have been expended and when the rate at which interest during construction accumulates is largest so it is important to minimize the duration of commissioning.

Table 4.1.4. User requirements and criteria related to Principle 2

Basic Principle 2: *Innovative Nuclear Energy Systems must represent an attractive investment compared with other major capital investments*		
User Requirements	Criteria	
	Indicator	Acceptance Limit
2.1 The total investment required to design, construct, and commission innovative nuclear energy systems, including interest during construction, must be such that the necessary investment funds can be raised.	Total investment.	Investment in INS enable a return comparable with or better than that required to deploy a competing energy technology of comparable size.
	Project construction and commissioning times.	Times comparable to alternative projects. Schedules met.
2.2 The Internal Rate of Return, IRR for investments in innovative nuclear energy systems, and the Net Present Value, NPV, of such investments shall be attractive compared with investments in competing energy technologies.	IRR NPV	Investor requirements met.
2.3 The risk of investment in innovative nuclear energy systems should be acceptable to investors taking into account the risk of investment in other energy projects.	Manageability of risks associated with environment, safety of nuclear installation, waste management, and proliferation resistance.	Environmental, safety, proliferation resistance, and waste management requirements set out in Sections 4.2 to 4.5 for INS and facilities met. Pre-licensing possible in country of origin (see also Section 4.6.2.2).
2.4 Innovative energy systems should represent a long-term investment opportunity.	Sustainability of INS Flexibility of INS to adapt to different circumstances.	Requirements & criteria for sustainability set out in Section 4.2 met. Availability of qualified suppliers. Ability to adapt technology to different plant sizes.

Recent construction times for reactor projects have been as short as 52 months (first concrete to criticality) and commissioning periods from first criticality to full power have been as short as 2–3 months for repeat projects. Thus, a construction period of 48 months is judged to be an achievable target, at least for reactors, within the near future. In due course, with innovation, use of in-shop modular construction, and for repeat plants, construction periods as short as 36 months should be achievable.

Economic User Requirement 2.2: *The Internal Rate of Return, IRR, for investments in innovative nuclear energy systems, and the Net Present Value, NPV, of such investments shall be attractive compared with investments in competing energy technologies.*

The requirement is expressed in terms of both internal rate of return and net present value to reflect the fact that in some regions INS will require private sector investment while in other regions INS will require government investment or guarantees. Private sector investors will be attracted by a competitive IRR, provided the IRR is commensurate with their judgment of associated risks. 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 than private sector investors. In either case short construction and commissioning times, which constrain project completion risks, as discussed above, and high plant availabilities, long plant lifetimes, well defined waste management and decommissioning costs, low O&M costs, which constrain plant performance risks, are all important in minimizing risk and hence in determining an acceptable rate of return. In the end the requirement is that the IRR/NPV must be attractive to the prospective investor.

Economic User Requirement 2.3: *The risk of investment in innovative nuclear energy systems should be acceptable to investors taking into account the risk of investment in other energy projects.*

Investment in energy technologies in general and nuclear energy systems in particular exposes the investor to potential losses resulting from project completion uncertainties, already discussed and to risks from safety failures (liability as well as loss of production and hence revenue), unacceptable environmental impacts, including, potentially, from inappropriate waste management or radiation protection practices that are only recognized after the fact, higher than expected decommissioning costs, and adverse public pressure. Thus, the requirements related to safety, waste management, proliferation resistance, and the environment set out in later sections of Chapter 4 must be met to provide investors with confidence that their investment is not unduly risky. Generally, construction and operation of a prototype or a first of a kind plant will provide confidence that technical risks have been covered and lay the foundation for pre-licensing in the country of origin, thereby further minimizing risk for larger scale deployment.

Economic User Requirement 2.4: *Innovative energy systems should represent a long-term investment opportunity*

All other things considered equal, investors will be attracted to investment markets that represent long-term opportunities where they too can benefit from learning. Thus, sustainability of INS systems is itself a desirable, if not absolute, requirement to attract investment. So, the requirements and criteria related to sustainability set out in Section 4.2 are also of economic importance. Sustainability is bolstered by the existence of qualified suppliers that can provide INS with confidence. Also, given the uncertainty about the future, as reflected for example in the wide range of possible future scenarios considered in the

SRES, INS should be sufficiently flexible to be able to evolve and adapt in a manner that provides competitive energy for as wide a range of plausible futures as possible.

4.1.5. Policy options and RD&D

The learning rate approach discussed above is useful also in discussions of long-term policy. It suggests two general categories of policy options. The first includes policies to speed progress down the learning curve, i.e., to speed the rate at which experience is accumulated in order that costs drop more quickly. The second category includes policies to steepen the learning curve by increasing the learning rate.

Policies in the first category – aimed at speeding progress down the learning curve – are based on the premise that people with limited planning horizons will tend to under-invest (from the long-term global perspective) in new energy technologies that are currently expensive.[22] Their purchasing decisions give no weight to the fact that, due to learning effects, these technologies have the potential to become important inexpensive clean contributors to the energy system. Advocates of solar power and wind power would consider their technologies to fall at least partly into this class, where consumers and companies, left to their own devices, are likely to under-invest relative to the long-term social interest. Where the market fails to serve perceived social interests, we all naturally turn to governments to compensate. This is the logic behind government subsidies, in all their myriad forms, for new technologies such as wind and solar, and it is the logic behind current calls by the nuclear industry in the US for government assistance on the first few next generation plants. And it is part of the logic behind government technology mandates – e.g., green certificates to show that by a given date, say, 10 percent of a country's electricity comes from renewable sources. In the first instance, subsidies will lower the consumer's price and encourage use. Expanded use means quicker progress down the learning curve. Government purchases directly increase use and thus speed progress down the learning curve. And mandates that force consumers to buy more of a new technology than economic considerations would warrant also increase use and accelerate progress down the learning curve.

Policies in the second category – aimed at increasing learning rates – focus on factors in addition to experience accumulation that might lead to cost reductions. Possibilities include RD&D investment, corporate structure, market structure, patent law, regulatory oversight, and education and training. If the impact of each of these on cost reductions (on the slope of the learning curve) were well understood, it would be possible to identify cost-effective government (or corporate) policies to steepen learning curves consistent with government (or corporate) objectives. Unfortunately, despite an expanding body of research, the impacts of such factors on cost reductions are not yet sufficiently clearly understood to prescribe here policies to reach target learning rates.

4.1.5.1. Reductions in costs and research, development and demonstration investment

Equation 1 above is a one-factor learning curve – cost reductions are a function only of cumulative capacity. To incorporate the effects of RD&D investments Kouvaritakis et al. [4.1-19] proposed a two-factor learning curve, with cumulative RD&D investments being the second factor. Miketa and Schrattenholzer [4.1-20] have modified Kouvaritakis et al.'s formulation by replacing cumulative RD&D with the notion of "knowledge stock," which

---

[22] This paragraph borrows extensively from reference [4.1-10].

includes RD&D expenditures but also takes into account depreciation and time lags. Clear quantitative empirical results are still elusive. Some qualitative insights are available from stylized model runs to test the sensitivity of policy recommendations to variations in assumed "learning by doing" rates (reflecting cost reductions due to experience accumulation) and "learning by searching" rates (reflecting cost reductions due to RD&D investments).

A quantitative illustration of learning by searching provided by Russian experts for sodium cooled fast reactors [4.1-21] is given in Figure 4.1.7. Cumulative investment in RD&D relative to the RD&D cost for the first design of a fast breeder reactor (BN-350) was selected as the "searching" experience indicator. The lines on Figure 4.1.7 correspond to a "learning by searching" rate of about 15%.

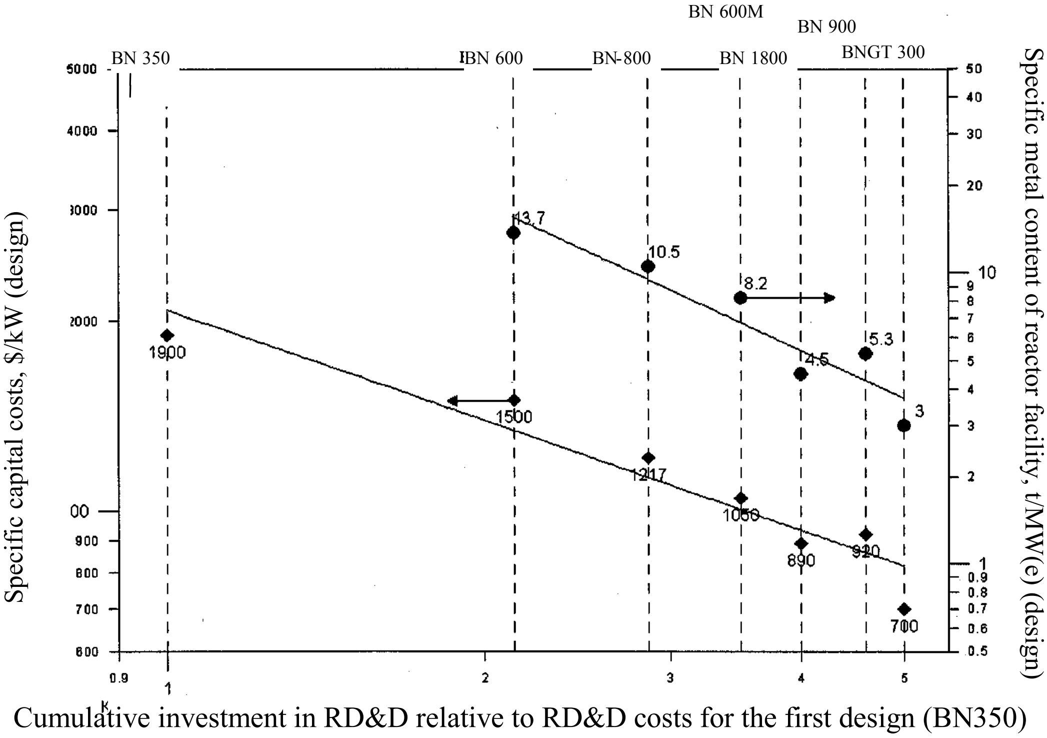


Fig. 4.1.7. Cost reductions for fast reactors of the BN series.

4.1.6. *Concluding remarks*

Innovative nuclear reactors and fuel cycles have the potential to make substantial contributions to meeting an increasing demand for energy. For INS, or indeed any energy source, to gain and grow market share they must be competitive with alternative sources of energy. INS must compete first and foremost on economics and so developers of such systems must learn from experience and introduce innovation to achieve cost reductions with time. For such learning to take place experience must be gained and to gain such experience the energy from INS must be cost competitive with energy from alternative sources.

In addition, innovative energy systems must represent an attractive investment to compete successfully in the capital market place with appropriate treatment of risk. To be cost competitive, cost reductions are required in capital costs, operating and maintenance cost, fuel costs and in total unit energy costs. Achieving such cost reductions will contribute to investor confidence. Limits on fuel costs in turn imply limits on the capital and operating cost of fuel cycle facilities, including mines, fuel processing and enrichment, fuel reprocessing and the decommissioning and long-term management of the wastes from these facilities. Meeting the requirements set out for safety, waste management, sustainability and environmental protection and proliferation resistance will contribute to risk reduction.

References to Section 4.1

[4.1-1] INTERNATIONAL PANEL ON CLIMATE CHANGE, Special Report on Emission Scenarios, A Special Report of Working Group III, Cambridge University Press, Cambridge (2000) (<http://www.grida.no/climate/ipcc/emission/index.htm>).

[4.1-2] LANGLOIS, L.M., MCDONALD, A., ROGNER, H-H., and VERA, I., "Energy System Expectations for Nuclear in the 21st Century: A Plausible Range", 10th International Conference on Nuclear Engineering (ICONE-10), Arlington, VA, USA, April 14-18, 2002.

[4.1-3] MCDONALD, A., RIAHI, K., and ROGNER, H-H., "Elaborating SRES Scenarios for Nuclear Energy", presented at the International Conference on Energy Technologies for post Kyoto Targets in the Medium Term, Risø National Laboratory, Denmark, 19-21 May 2003.

[4.1-4] WRIGHT, T.P., Journal of Aeronautical Science **3** (1936) 122.

[4.1-5] DUTTON, J.M., and THOMAS, A., Treating progress functions as a managerial opportunity, Academy of Management Review **9** (1984) 235.

[4.1-6] MCDONALD, A., and SCHRATTENHOLZER, L., Learning rates for energy technologies, Energy Policy **29** (2001) 255.

[4.1-7] MESSNER, S., and STRUBBERGER, M., User's guide for MESSAGE III, WP-95-69, International Institute for Applied Systems Analysis, Laxenburg, Austria (1995).

[4.1-8] INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, WORLD ENERGY COUNCIL, Global Energy Perspectives to 2050 and Beyond, WEC, London, (1995).

[4.1-9] GRUBLER, A., Technology and Global Change, Cambridge University Press, Cambridge, (1998).

[4.1-10] MCDONALD, A., and SCHRATTENHOLZER, L., Learning Curves and Technology Assessment, International Journal of Technology Management **23** Nos 7/8 (2002) 718.

[4.1-11] ARGOTE, L., Organizational Learning: Creating, Retaining and Transferring Knowledge, Kluwer, Dordrecht, Netherlands (1999).

[4.1-12] DUFFEY, R.B., Innovation in Technology for the Least Product Price and Cost: A New Minimum Cost Relation for Reductions During Technology Learning, accepted for publication in International Journal of Energy and Technology Policy.

[4.1-13] DUFFEY, R.B., and SAULL, J.W., Know the Risk: Learning from Errors and Accidents: Safety and Risk in Today's Technology, Butterworth-Heinmann College, MA, USA, ISBN 0750675969 (2002).

[4.1-14] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology Review 2002, IAEA, Vienna (2002).

[4.1-15] EUROPEAN COMMISSION, ExternE, Externalities of Energy New Results, DGXII Science, Research and Development, L-2920, EC, Luxembourg (1998).

[4.1-16] OECD NUCLEAR ENERGY AGENCY, OECD INTERNATIONAL ENERGY AGENCY, Projected Costs of Generating Electricity: Update 1998, OECD/IEA, Paris (1998).

[4.1-17] INTERNATIONAL ATOMIC ENERGY AGENCY, Economic Evaluation of Bids for Nuclear Power Plants 1999 Edition, Technical Reports Series No. 396, IAEA, Vienna (2000).

[4.1-18] TRAINER, T., Can Solar Sources Meet Australia's Electricity and Liquid Fuel Demand?, International Journal of Global Energy Issues **1** No.1 (2003) 78.

[4.1-19] KOUVARITAKIS, N., SORIA, A., and ISOARD S., Modeling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching, International Journal of Global Energy Issues **1** No. 1-4 (2000) 104.

[4.1-20] MIKETA, A., and SCHRATTENHOLZER, L., Optimizing R&D expenditures on energy technologies using a stylized energy supply model, submitted for publication (2002).

[4.1-21] ZRODNIKOV, A.V., OUSSANOV, V.I., AND IOUGAI, S.V., Use of the 'Learning Curves' for the Assessment of the Fast Sodium Reactor's Competitiveness, to be published in Atomnaya Energiya.

4.2. Sustainability and environment

4.2.1. Introduction

4.2.1.1. INPRO and the environment

Protection of the environment is a major consideration in the processes for approving industrial activities in many countries. The level of societal concern for the environment internationally is clearly indicated in documents reflecting international consensus, notably the report of the Bruntland Commission [4.2-1], the Rio declarations on sustainable development [4.2-2], and a Joint Convention of the IAEA [4.2-3].

The purpose of INPRO is to support the development of nuclear technology that has several important characteristics, namely that it should be able to meet the global energy needs of the 21st century, be economical, be safe, be sustainable, and be proliferation resistant. All of these characteristics are related to environmental quality as discussed briefly below. Waste management is treated in Section 4.4.

Although INPRO deals with innovative systems that may be implemented in the next 50 years, it needs to be emphasized that the time frame for considering environmental effects, while difficult to define, is certainly far longer than the time frame considered for implementation.

Economy

To properly evaluate the economic viability and comparative economic advantage of a technology, it is imperative that all costs of the technology be considered. This will include the costs associated with protecting human health and the environment. Moreover, the so-called external costs, those borne by society because of residual health and environmental effects, but not charged to the producer, should also be evaluated. In the past, many of these costs have been left unaccounted for. The failure to "internalize" environmental costs is increasingly recognized and the economics of future technologies should include them, though damage to the environment may still not be fully compensated.

Safety

Separate tasks of INPRO deal specifically with safety and waste management (Sections 4.3 and 4.4) but address, almost exclusively, radiological effects on humans and the risk of nuclear accidents with the potential to release radioactive material. The scope of environmental aspects is much broader, including potential effects on non-human environmental components and effects of non-radiological stressors. Moreover, the standards and methods employed in evaluating and managing environmental effects are generally different from those used in establishing nuclear safety.

In the past the International Commission on Radiological Protection (ICRP) has taken the position, that "the standards of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk" [4.2-4]. This position has come under increasing scrutiny and so the ICRP has recently formed a Task Group on Environmental Effects to suggest a framework for the assessment of the impact of ionizing radiation in the environment, and protection of the environment against its harmful effects.

Sustainability

The present generation should not compromise the ability of future generations to fulfill their needs and should leave them a healthy environment. Nuclear power should support sustainable development by providing much needed energy with relatively low burden on the atmosphere, water, and land use. Further development of nuclear power will help to alleviate the environmental burden caused by other forms of energy production, particularly the burning of fossil fuels.

The 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. Efficient and effective use of resources will also be necessary. Moreover, improvement of the technology should include improvement of its environmental aspects to a degree consistent with their importance to society and with the potential environmental performance of competing technologies.

Proliferation resistance

Proliferation resistance is unquestionably an important issue but it is explicitly dealt with in a later section of this report and is not specifically considered in developing the user requirements under this task.

4.2.1.2. Objectives

The objectives of this section are twofold:

1) To specify and discuss the Basic Principles and User Requirements for environmental performance of innovative nuclear energy systems; and
2) To describe Requirements for methods of assessing the environmental performance of proposed innovative nuclear energy systems.

The principles and requirements for the environmental performance of INS are discussed in detail in Sections 4.2.2, 4.2.3, 4.2.4, and 4.2.5, and summarized in Table 4.2.1.

4.2.1.3. Environmental effects

The term "environment" is defined within the laws and regulations of various jurisdictions. It generally includes the following components: human beings; non-human biota; abiotic components, including soil, water and air, natural resources and landscape; and interactions among these components.

Environmental effects covered by this section include: physical, chemical or biological changes in the environment; health effects on people, plants and animals; effects on quality of life of people, plants and animals; effects on the economy; use/depletion of resources; and cumulative effects resulting from the influence of the system in conjunction with other influences on the environment.

Both radiological and non-radiological effects as well as trade-offs and synergies among the effects from different system components and different environmental stressors need to be considered. For the purposes of INPRO priority is given to the effects important for:

- Determining that the nuclear energy system adheres to the basic principles; and
- Inter-comparing proposed components and nuclear energy systems as a whole with respect to their technical environmental performance as part of an overall INPRO technical evaluation.

Table 4.2.1. Basic Principles, User Requirements and Criteria for nuclear energy systems

Basic Principle 1: Acceptability of Environmental Effects *The expected (best estimate) adverse environmental effects of the innovative nuclear energy system must be well within the performance envelope of current nuclear energy systems delivering similar energy products.*		
User Requirements	Criteria	
	Indicator	Acceptance Limit
1.1 *The environmental stressors from each part of the system over the complete life cycle must be controllable to levels meeting or superior to current standards.*	L_{St-i} , level of stressor *i.*	$L_{St-i} \leq S_{i,}$ where S_i is the standard for stressor I.
1.2 *The likely adverse environmental effects attributable to the nuclear energy system should be as low as reasonably practicable, social and economic factors taken into account.*	E_{ae-I}, adverse environmental effect.	$E_{ae-i} \leq L_{ALARP}$ ALARP: as low as reasonable practicable.

Basic Principle 2: Fitness for Purpose *The innovative nuclear energy system must be capable of contributing to energy needs in the future while making efficient use of non-renewable resources.*		
User Requirements	Criteria	
	Indicator	Acceptance Limit
2.1 *The system should be able to meet a significant fraction of the world's energy needs during the 21st century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the energy system.*	F_{ci} : Fuel i consumed in 100 yrs (Mg).	$F_{ci} \leq (F_{pr-i} + F_{ri})$ F_{pr-i} : Fuel i proven reserves (Mg), and $F_{ri;}$ Fuel i reprocessed in 100 yrs (Mg).
	M_{ci} : Critical material i consumed in 100 yrs (Mg).	$M_{ci} \leq M_{pri}$ M_{pri} : Proven reserves of critical material i (Mg)
	$B_{up} = E / U$ B_{up} : burnup. E : provided energy (MWd). U: consumed fissile material (Mg).	$B_{up} > B_{up}$Ref B_{up}Ref : reference burnup.
2.2 *The energy output of the system must exceed the energy required to implement and operate the system within an acceptably short period.*	T_{EQ} : time required to match the total energy input with energy output (yrs).	$T_{EQ} \leq k \cdot T_L$ T_L : intended life cycle of nuclear system. $k < 1$

4.2.2. Basic principles

4.2.2.1. Principle 1 – Acceptability of expected adverse environmental effects

The expected (best estimate) adverse environmental effects of the innovative nuclear energy system must be well within the performance envelope of current nuclear energy systems delivering similar energy products.

Adverse environmental effects may arise from any component and life cycle stage of the nuclear energy system. Moreover, the design and operation of one component of the system can have a major influence on the environmental effects of other components. Therefore, the environmental performance of a proposed system should be evaluated as an integrated whole.

The expected adverse environmental effects must be within the current regulatory guides, namely those prevailing at the time of the assessment, which is certainly the case for the existing nuclear energy systems. See, for example, the European Union ExternE study [4.2-5], which has examined the impacts of alternative energy production systems and has shown that the existing nuclear generation has a low relative impact. There is an expectation that the environmental performance of an INS will be even better than that of an existing system.

Environmental performance analyses on nuclear energy systems should not be used in comparisons with other energy systems unless they have both been analyzed to a similar depth.

The holistic approach recommended for the environmental analysis within INPRO is illustrated in Figure 4.2.1. The various components and flows included in the picture are described in following sections.

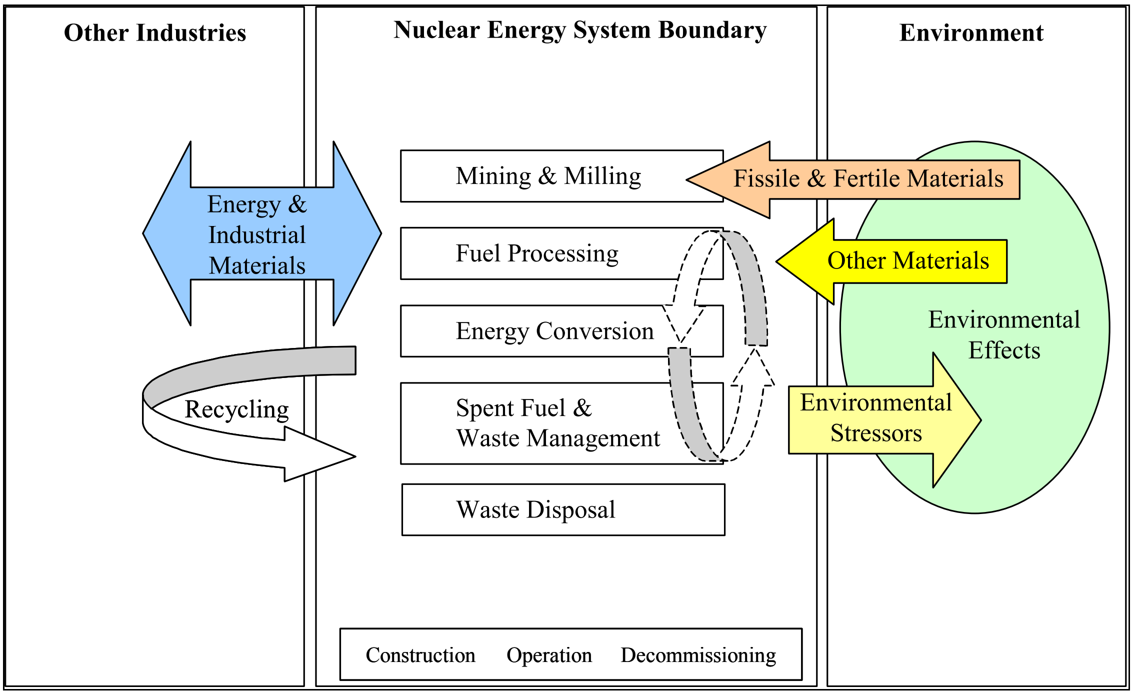


Figure 4.2.1. Holistic approach for environmental assessment.

4.2.2.2. Principle 2 – Fitness for purpose

The innovative nuclear energy system must be capable of contributing to energy needs in the future while making efficient use of non-renewable resources.

To be acceptable environmentally the system must be sustainable and not run out of important resources part way through its intended lifetime. These resources include fissile/fertile material, water (when supplies are limited or quality is under stress) and other critical materials. The system should also use them at least as efficiently as acceptable alternatives, both nuclear and non-nuclear. Even in the absence of a viable alternative the best use possible is to be made of non-renewable resources.

4.2.3. User requirements for nuclear energy systems

The requirements presented are divided into two categories as follows :

1) User Requirements on the nuclear energy system; and
2) User Requirements on the methods used to assess the environmental performance of the nuclear energy system.

The first category is discussed in the following subsections of this section, and the second in Section 4.2.4.

4.2.3.1. Controllability of environmental stressors

The environmental stressors from each part of the system over the complete life cycle must be controllable to levels meeting or superior to current standards.

Any energy system will inevitably introduce stressors to the environment, such as radionuclides or non-radioactive chemicals, and use of resources, with potentially adverse environmental effects on a local, regional or even global scale. For example, carbon emissions from fossil fuels, if current tendencies are continued, will grow up to 60 % by 2020 and could be tripled by 2050. The operators of nuclear facilities and processes will be responsible for controlling the stressors from these facilities. One function of the design of an innovative energy system, i.e. a design criterion for such systems, is to provide controllability of all stressors throughout the nuclear energy system.

All stressors must be controllable to levels meeting or superior to the current standards (those prevailing at the time the energy design is being assessed). Each standard could be the same, less demanding, or more demanding than today’s standard depending on the state of scientific understanding of the environmental effects as well as stakeholder perceptions.

4.2.3.2. Adverse effects as low as reasonably practicable

The likely adverse environmental effects attributable to the nuclear energy system should be as low as reasonably practicable, social and economic factors taken into account.

An INS would be held to higher environmental standards than existing nuclear energy systems. It should be recognized, however, that in some cases the enhanced environmental performance of a particular facility or process may be offset by increased adverse effects elsewhere in the energy system. Therefore, this User Requirement (a) applies the philosophy of achieving the best performance reasonably practicable to the entire INS, (b) extends it to all adverse environmental effects, not only radiological effects on humans, and (c) continues to recognize that costs incurred to enhance environmental performance should not be greatly disproportionate to the benefit.

The basic philosophy is that the nuclear energy system should be designed according to modern engineering principles. Then the design should be reviewed to verify that the risk to the environment is as low as reasonably practicable, social, and economic factors taken into account (ALARP).

4.2.3.3. Consistency with resource availability

The system should be able to meet a significant fraction of the world's energy needs during the 21st century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the energy system.

To establish that this requirement will be met, careful consideration must be given to the implications for the world's available resources with appropriate choice of the boundary of the system (see Figure 4.2.1).

A major factor would be the (net) depletion of fissile and fertile material (e.g., U, separated Pu, Th). Assumptions regarding extraction technologies, breeding rates, etc., should be carefully reviewed for practicality and other non-renewable resources considered. Depletion of resources by other industries and their importance for these industries should also be taken into account.

4.2.3.4. Adequate net energy output

The energy output of the system must exceed the energy required to implement and operate the system within an acceptably short period.

The net energy output of the system is the usable energy produced by the system over and above the energy required to establish and operate the system over its intended life cycle. The net energy balance output should turn to positive in an acceptably short period. Stakeholder consensus should determine the target length of time (acceptance limit) for the energy balance to turn positive. A study on nuclear energy systems completed by the World Nuclear Association (WNA) [4.2-6] shows that the materials and energy used today by a nuclear energy system is far less than the energy produced (by a factor of 20 or more). For INS it is expected the ratio will be even greater because of more efficient fuel utilization, simplified designs and the use of improved materials and construction techniques.

4.2.4. User requirements for assessment methods

4.2.4.1. Consider all factors

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.

Figure 4.2.2 illustrates the factors involved in an assessment of environmental effects of a project. The first factors to be identified are the sources of stressors: power plants, auxiliary facilities, etc. Each source has associated stressors: releases of radioactivity, chemical toxins, etc. Each stressor can be introduced in the environment and spread through different pathways: air, surface water, etc. Each pathway has associated receptors: humans, aquatic ecosystems, etc. Each receptor may have different endpoints or possible areas that can be affected by the stressors: human beings can be affected in their health, their property values, etc. Finally, the effects are the end points for each of the receptors from all of the stressors. To be practical when applied to a conceptual design, only key relevant factors should be carried through detailed analysis. Further simplification may be possible when the objective is only to inter-compare systems, so common factors may be excluded.

A complete overview of all the relevant factors that must be taken into account, can be found in IAEA publications such as Refs [4.2-7] and [4.2-8].

Nuclear energy systems for INPRO would likely be evaluated without any specific sites for their components. So it may be necessary to postulate some important site characteristics or an envelope of site characteristics and no conclusions regarding environmental performance of systems should be taken out of context of the assumptions made about the site.

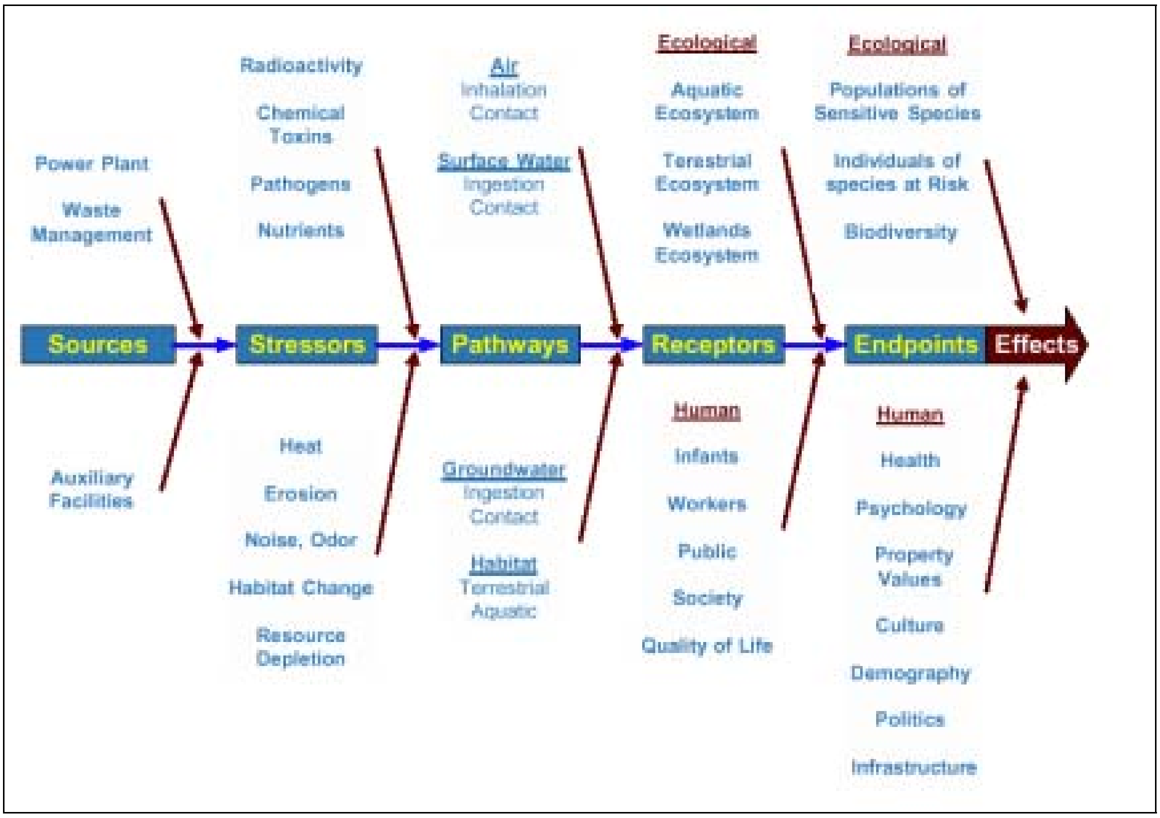


Figure 4.2.2. Factors in environmental assessment.

4.2.4.2. Complete system approach

The environmental performance of a proposed technology is to be evaluated as an integrated whole by considering the likely environmental effects of the entire collection of processes, activities and facilities in the energy system at all stages of its life cycle.

All components of the energy system may cause interacting environmental effects. Conclusions drawn from considering an individual component could be invalid for the system as a whole. Therefore, trade-offs and synergies need to be considered.

Various components of the energy system may be located in different jurisdictions with different responses to environmental stressors and different ways of looking at environmental effects. This should not prevent an objective evaluation of the system as a whole, regardless of national boundaries.

Notwithstanding the requirement that the whole system be considered, it is appropriate to make justifiable simplifications as discussed in Section 4.2.5.

4.2.4.3. Complete material flow

All important material and energy flows in, out, and through the system must be accounted for.

The material and energy flows can be categorized as follows (Figure 4.2.2):

- Flows between components of the system;
- Flows from the natural environment directly into the system;
- Flows to and from industrial sectors outside the system; and
- Flows from the system into the environment.

Analysis of net material flows has two purposes: (a) evaluating the potential impact of environmental stressors associated with the material flows, and (b) providing a measure of the depletion of corresponding resources.

The flows of matter and energy, net of any internally recycled quantities, may be substantial. The production of these materials will have associated adverse environmental effects not directly accounted for within the system itself but which should be taken into account. Otherwise, comparison of different energy systems would be based on incomplete information.

The depletion of non-renewable resources must be analyzed to assure that the intended energy production and the time over which the system must operate are consistent with available resources, with the uses of these resources outside of the energy system taken into account.

4.2.4.4. Non-routine events

The likely significance of adverse environmental effects due to events outside of normal operations throughout the system should be evaluated.

Accidents with severe radiological environmental damage have a very low probability in modern nuclear energy systems. Nevertheless, the consequences of such potential accidents continue to affect the acceptability of nuclear technology. Nuclear safety is aimed at ensuring that the probability of effects to the health of human beings is kept acceptably low; however, consideration of the effects on other parts of the environment is at a relatively early stage of development. So it would seem necessary that these environmental effects be given more consideration than is done presently. Understanding of potential environmental effects of severe accidents should be improved. Such effects could involve different source terms, different pathways, different stressors, and different endpoints than considered in traditional safety analysis.

Non-routine events affecting the environment may occur in any part of the nuclear energy system. Less severe but more probable events are for the most part not considered by traditional nuclear safety formalisms, but should be included in a complete environmental evaluation.

4.2.5. Methods of assessment

4.2.5.1. Material and energy accounting

Life cycle assessment

Life cycle assessment (LCA) [4.2-9] is a systematic method used extensively for evaluating environmental effects of a technology or production process from the extraction of raw material to the disposal of wastes (cradle to grave). LCA requires the identification and quantification of emissions and material consumption at all stages of the entire product life cycle that affect the environment [4.2-10], and includes the estimation of emissions from both direct sources within the system and indirect sources, such as those associated with supplying the energy for construction materials of physical structures within the system. It may be appropriate to treat only the main contributors to potential environmental effects to differentiate between proposed generations technologies. This procedure has been used by the Swiss LCA study of the environmental inventories of future electricity and heating systems (time horizon 30 years) [4.2-11], [4.2-12].

Accounting for materials throughout the system in a life cycle inventory (LCI) analysis provides necessary input. Significant additional information is, however, required. Complete environmental assessment would normally be applied to a local project on a particular site and would include site-specific factors like local resource depletion, effects on landscape, local infrastructure, culture and heritage, and political efficacy. Such effects are addressed more effectively by other techniques. However, it is unlikely that they would differentiate between technological or generic design options as required by INPRO, and so may not need to be included in detailed analysis, but omissions must be well founded. Such local and, in part, non-technical issues are best left for the stage of future implementation.

Addressing effects due to (low-probability) accidents is more difficult. The effects due to low-probability accidents can, in principle, be addressed using Probabilistic Safety Analysis (PSA). It is assumed here that such aspects are fully taken into account by the safety requirements of the INPRO project and that the probability of exposing the environment to harmful effects due to accidents will be kept sufficiently low for all fuel cycles considered by INPRO and may be ignored in the LCA. However, when the effects of hypothetical non-routine events would be different for different nuclear systems, their associated environmental aspects should be addressed in a manner consistent with Section 4.2.4.4.

Material flow assessment

Material flow assessment (MFA) [4.2-11], [4.2-13] was originally developed, beginning in the 1970s, as an instrument to control the use of resources including dispersive losses of hazardous compounds. It is a promising tool for the assessment of environmental impacts and the sustainability of various power generation options. MFA has proven to be useful in indicating potential areas of improvement within a system and for evaluating the sensitivity of a system to enveloping scenarios. MFA is complementary to and supportive of LCA. Its important feature is the capability to analyze the dynamics as well as the equilibrium state, which is important for comparing fuel cycles. In particular, the supply and demand of special materials during any initial transient phase of a fuel cycle may need to be considered. To use

MFA it may be necessary that flows and inventories be normalized to a unit of production (e.g., electrical energy).

In principle, MFA must consider all materials in the system. In practice, simplifications arise from a number of factors:

- Only flows of materials and resources that would differentiate options and designs need to be included in the analysis;
- Simplification of the models may enhance transparency and usability of the analyses. Analytical muscle should be applied preferentially to those material balances of most importance to making the required comparisons; and
- Flow of a material may be dominated by flow in a particular component of the system.

Relation to environmental indicators

LCA and MFA do not constitute a complete assessment method. The methods used are often oversimplified and require subjective judgments, which diminish their technical rigor. They cannot be considered fully satisfactorily for how they address specific nuclear issues for the reasons set out below.

The material quantities and flows are not usually a direct measure of environmental effect. The results of environmental assessment are multiple effects caused by multiple stressors. Two principal options exist for inter-comparing systems: (a) express all of the effects on an equivalent basis, weight them according to perceived importance, and sum the weighted measures to obtain a single measure of environmental detriment; or, (b) quantify each effect according to its own suitable measure and apply a multivariate decision-making process.

In either case, some development work will be required to bring the method to the operational stage for the specific purposes of INPRO.

4.2.5.2. Environmental effects

Figure 4.2.3 is a diagram of analytical steps involved in the evaluation of the life cycle environmental performance of a nuclear energy technology. Each circle in the diagram represents a step, with the double circle representing the overall evaluation. The arrows represent information transfer, which includes identities, quantities, and flow rates of materials and energy. The evaluation includes the following:

- Identification of the materials of primary interest: fertile and fissile materials (e.g., U^{235}, Pu^{239}) as well as other strategic materials. The time dependent net flow is evaluated against proven reserves, inventories and production rates. In particular, the use of materials during an initial transient in establishing an equilibrium fuel cycle must be accounted for and their recycling credited in the assessment;
- Materials that pose a particular 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 the environmental pathways;
- Identification of chemical materials of particular environmental significance. The environmental risks of their manufacture and use within the system are assessed in parallel with those of radioactive materials;

- Assessment of the environmental effects of discharges of radioactive and chemically hazardous materials and heat during normal and outside of normal operation; and
- Evaluation of the extent of use and depletion of natural resources (e.g., water and land) and of energy use by all parts of the system.

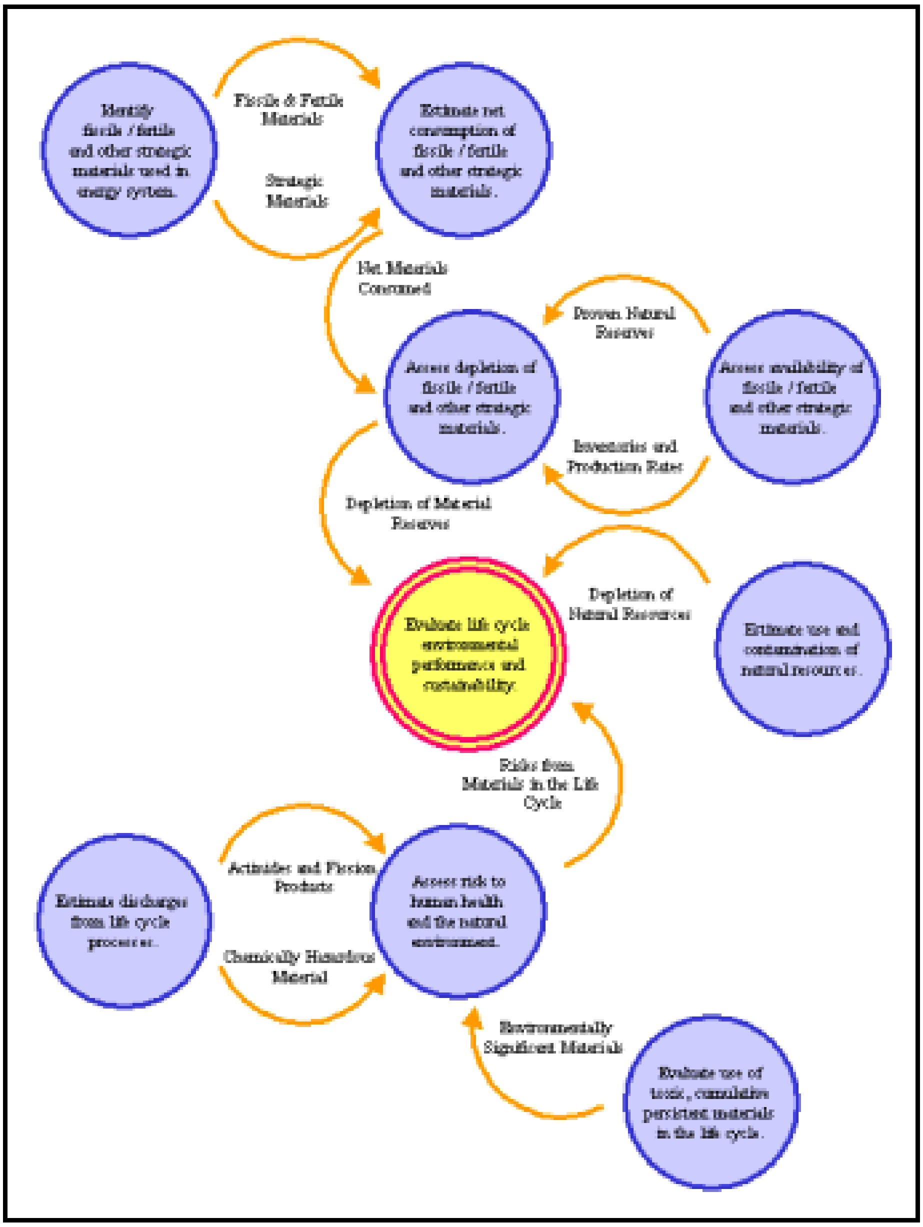


Figure 4.2.3. Information diagram for application of MFA/LCA to evaluation of environmental performance.

4.2.6. Further development

Development work should be focused on adapting LCA and FMA techniques to the specific requirements of INPRO. Some suggestions are mentioned below.

4.2.6.1. Material accounting methods

The major materials and energy forms should be identified and methods specified for estimating all their flows. Figure 4.2.1 presents guidance on information requirements.

Some emissions may be neglected but their exclusion would need to be justified. Potential releases from events outside of normal operation are important. Therefore it is necessary to consider the following factors in the MFA: (a) the flow of material through all stages of the life cycle; (b) the inventories of the material at each stage; (c) the time over which the materials remain accessible to the environment in both transient and steady state conditions; (d) the mobility of the materials at the various stages.

These considerations will influence the design of the systems towards early safe disposal or destruction of hazardous materials, and planned operations toward segregation of materials to reduce the total volumes of contaminated material and in preparation for their disposal or destruction.

It may be necessary to develop a comprehensive material and energy flow model of the system with modules for various stages, which can be customized and linked to simulate a number of different life cycles.

4.2.6.2. Measures of environmental detriment

A systematic and consistent method of measuring environmental detriment of materials and energy exchanged between the system and the environment is essential on a local, regional, national or global scale. In some cases it is important to consider maximal effects (the critical group concept), while in other cases it is more relevant to consider averaged or cumulative effects. The measures of detriment should be practical for the uses in INPRO as well as sufficiently indicative of the environmental effects. Alternative approaches are: (a) use of commensurate values for all stressors with weighting factors or (b) multivariate analysis. In both cases decision-making process will be subjective to some extent. A suitably comprehensive consultation process among stakeholders will be necessary to provide the required judgments for a broadly acceptable comparison.

It may be necessary to take external environmental costs into account in comparing nuclear energy systems (see Section 4.2.1.1). If so, the method for calculating these costs would need to be adapted to future economic conditions.

4.2.7. Concluding remarks

Environmental aspects are related to all characteristics of innovative reactors and fuel cycles: safety, waste management, economy, proliferation resistance, sustainability and the ability to meet the global energy needs of the 21st century. The environmental performance of the energy system is vital to its future acceptability and is an important aspect of the evaluation of proposed INPRO technologies.

Two Basic Principles have been identified:

1) *The expected (best estimate) adverse environmental effects of the nuclear energy system must be well within the performance envelope of current nuclear energy systems delivering similar energy products.*

2) *The nuclear energy system must be capable of contributing to the energy needs in the future while making efficient use of non-renewable resources.*

Simplifications may be introduced into the particular requirements for screening and evaluation of INPRO technologies. Emphasis should be placed on those effects that would distinguish between proposed technologies. These are primarily related to material and energy flows within, into and out of the system (see Figures 4.2.1 and 4.2.3).

The techniques of life cycle assessment and materials flow assessment should be pursued. Recommendations for particular development activities have been presented in the previous section.

A process should be put in place to establish stakeholder consensus on key matters including specific criteria for screening, measures of environmental detriment, weighting factors (as appropriate), and value judgments required for multivariate analysis (as appropriate).

An overall conclusion is that the basic tools to screen and effectively inter-compare INPRO technologies are available. Development of these tools is required to adapt and extend them for the particular task.

References to Section 4.2

[4.2-1] BRUNTLAND COMMISSION, World Commission on Environment and Development, “Our Common Future”, Oxford University Press, Oxford (1987).

[4.2-2] UNITED NATIONS, Conference on Environment and Development, Vol. I, Resolutions Adopted by the Conference (United Nations publication, Sales No. E.93.I.8), Rio de Janeiro (1992).

[4.2-3] INTERNATIONAL ATOMIC ENERGY AGENCY, The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, IAEA, Vienna (1997).

[4.2-4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford (1991).

[4.2-5] EUROPEAN COMMISSION, ExternE, Externalities of Energy, DGXII Science, Research and Development, JOULE Programme Reports, Volume 1: Summary Report (EUR 16520 EN), EC (1996).

[4.2-6] WORLD NUCLEAR ASSOCIATION, Energy Analysis of Power Systems, WNA, London (2003).

[4.2-7] INTERNATIONAL ATOMIC ENERGY AGENCY, Health and Environmental Aspects of Nuclear Fuel Cycle Facilities, IAEA-TECDOC-918, Vienna (1996).

[4.2-8] INTERNATIONAL ATOMIC ENERGY AGENCY, Health and Environmental Impacts of Electricity Generation Systems: Procedures for Comparative Assessment, Technical Reports Series No. 394, IAEA, Vienna (1999).

[4.2-9] INTERNATIONAL STANDARDS ORGANIZATION, ISO 2000, International Standard ISO 14042 — Environmental management — Life cycle assessment — Life cycle impact assessment, ISO 14042:2000(E), ISO, Geneva (2000).

[4.2-10] VAN DEN BERG N. W., et al., Beginning LCA; A guide into environmental life cycle assessment, Centre of Environmental Science, Leiden University, Leiden (1995).

[4.2-11] DONES, R., et al., Environmental Inventories for Future Electricity Supply Systems for Switzerland, PSI Report No. 96-07, Villigen, Switzerland (1996).

[4.2-12] GANTNER U., et al., Options for New Swiss Energy Supply Strategies, PSI Annual Report 1998, Annex IV, Villigen, Switzerland (1999) 11-21.
German report: "Perspektiven der zukünftigen Strom- & Wärmeversorgung für die Schweiz – Ökologische und ökonomische Betrachtungen", PSI Report Nr. 01-12, Villigen, Switzerland (2001).

[4.2-13] BRINGEZU, S., et al., Eds. Analysis for Action: Support for Policy towards Sustainability by Material Flow Accounting Proceedings of the ConAccount Conference 11-12 Sept., 1997, Wuppertal Special 6. 1997, Wuppertal Institute, Wuppertal (1997).

4.3. Safety of nuclear installations

4.3.1. Introduction and background

Safety principles and user requirements for safety of innovative reactors and fuel cycle facilities have been established taking into account the large body of work that exists dealing with the safety of reactors and facilities currently in operation and previous work on establishing requirements for next generation reactors.

4.3.1.1. Existing requirements

The IAEA has recently updated safety requirements that define the elements necessary to ensure the safety of nuclear power plants [4.3-1, 4.3-2]. On the national level, various utility groups have developed corresponding User (or Utility) Requirements Documents supported by experience from construction, licensing and operation of nuclear power plants over the past four decades (representing over 10,000 reactor-operating years). "Reactor safety requirements" documents have been prepared for evolutionary and advanced designs by organizations such as EPRI (Advanced Light Water Reactor Utility Requirements Document – ALWR-URD), Japanese and Korean Utilities (JURD and KURD) and the European Utilities (European Utility Requirements – EUR). They were authored largely by electricity-generating utilities. They arose from well-characterized reactor designs, reflected operating experience and formed the basis for development of evolutionary designs.

In September 1997 the IAEA [4.3-3] presented an overview of these utility documents and summarized the essence of the requirements as follows:

- A design life of 60 years;
- Reliable and flexible operation, with high overall plant availability, low level of unplanned outages, short refuelling outages, good controllability (e.g., 100–50–100% load following capability), and operating cycles extended up to 24 months;
- Increased margins to reduce sensitivity to disturbances and the number of safety challenges;
- Improved automation and man-machine interface which, together with the increased margins, provide more time for the operator to act in accident/incident situations, and reduce the probability of operator errors;
- Core damage frequency less than 10^{-5} per reactor-year and cumulative frequency of large releases following core damage less than 10^{-6} per reactor-year; and
- Design measures to cope with severe accidents.

In one specific area, there is a distinct difference between requirements for Europe and for the United States. This difference is attributed to the higher population density in Europe leading to lower release targets for EUR as follows:

- To limit emergency protection actions beyond 800 m from the reactor during early releases from the containment to a minimum;
- To avoid delayed actions (temporary transfer of people) at any time beyond about 3 km from the reactor;
- To avoid long term actions, involving permanent (longer than 1 year) resettlement of the public, at any distance beyond 800 m. from the reactor; and

- To ensure that restrictions on the consumption of foodstuffs and crops will be limited in terms of time and ground area.

4.3.1.2. Future requirements

The scope of the INPRO project covers nuclear reactors expected to come into service in the next 50 years, together with the associated fuel cycles. It is recognized that a mixture of current, evolutionary, and innovative designs will be brought into service and co-exist within this period. The recently published 'Three Agency Study' [4.3-4] provides an overview of current trends in the development of INS. The range of reactor systems having innovative design features includes water-cooled, gas-cooled, liquid metal-cooled systems and molten salt reactors of various sizes to be used for various purposes.

It is generally believed that for wide-spread and long-term use of nuclear power to be sustainable, a nuclear fuel strategy utilizing, at least as a component, breeding, reprocessing and recycling of fissile material will be required. In some countries or regions and for intermediate time scales innovative once-through strategies featuring improved safety, proliferation resistance and physical protection will be followed. Ultimately, however, the development and implementation of innovative reactors and fuel strategies will be based on closed fuel cycles that make better use of uranium and thorium resources.

User requirements for future nuclear installations represent an idealization of what is desirable in safety taking into account both national/regional trends and what is likely to be technologically achievable. INPRO requirements also encompass the potential interests of developing countries and countries in transition in the development of small and medium size nuclear power plants for various purposes. Further, they include long-term interests of both industrialized and developing countries in alternative fuel cycles. As the time horizon of these requirements is several decades, they represent a vision of the safety of nuclear installations in the future.

Consideration of future user requirements raises two issues: What will be the views of users in the future? How will technology change?

Users of innovative nuclear reactors and fuel cycle installations will likely encompass more than electricity generating companies, e.g., district heating companies, desalination companies, as well as a range of conventional industries. Future users would also include developing countries and countries in transition, so an attempt has been made to anticipate what an informed user might require.

It is difficult to anticipate or factor in step changes in technology, so INPRO has extrapolated current trends. Several levels of user requirements exist, from general to specific. A vendor of a given reactor design is expected to meet all user requirements at all levels that are specific to that reactor type and exceptions, even at the detailed level, are unusual. On the other hand, while, existing nuclear fuel cycle installations generally meet high standards of safety, currently there are no widely accepted user requirements for them.

Today's nuclear safety standards and requirements reflect a present consensus on the current status rather than a forecast of the status several decades ahead. As technology and scientific knowledge advance continuously, nuclear safety requirements are expected to change.

4.3.2. General approach to safety

4.3.2.1. General safety objective

There is a worldwide consensus on the **General Nuclear Safety Objective** [4.3-5], which is:

To protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards.

This general safety objective is equally valid for innovative reactors and fuel cycle facilities as it is for existing systems. It leads to two complementary safety objectives, an objective for radiation protection and a technical objective. The two are interdependent.

The radiation protection objective is to ensure that in all operational states exposures to radiation are kept below prescribed limits and as low as reasonably achievable, economic and social factors taken into account (ALARA) and to ensure mitigation of the radiological consequences of accidents.

The technical safety objective is to take all reasonably practical measures to prevent accidents and to mitigate their consequences, should they occur; to ensure with a high level of confidence that, for all possible accidents taken into account in the design of the installation, including those of very low probability, any radiological consequences would be minor or below prescribed limits; and to ensure that the likelihood of accidents with serious radiological consequences is extremely low.

4.3.2.2. Basic safety functions

For nuclear reactors, fundamental safety functions are to: control reactivity; remove heat from the core; and confine radioactive materials and shield radiation.

For fuel cycle installations (including spent fuel storage at reactor sites), they are to: control sub-criticality and chemistry; remove decay heat from radio nuclides; and confine radioactivity and shield radiation.

To ensure that the fundamental safety functions are adequately fulfilled, an effective defence-in-depth strategy should be implemented, combined with an increased use of inherent safety characteristics and passive systems in nuclear designs.

4.3.2.3. Defence-in-depth

Defence-in-depth provides an overall strategy for safety measures and features of nuclear installations [4.3-6], [4.3-7]. The strategy is twofold: first, to prevent accidents and, second, if prevention fails, to limit their potential consequences and prevent any evolution to more serious conditions. Accident prevention is the first priority. The rationale for the priority is that provisions to prevent deviations of the plant state from well-known operating conditions are generally more effective and more predictable than measures aimed at mitigation of such departure, because the plant performance generally deteriorates when the status of the plant or a component departs from normal conditions. Thus, preventing the degradation of plant status and performance generally will provide the most effective protection of the public and the environment. For INS the effectiveness of preventive measures should be enhanced compared with existing installations.

Ensuring the independence of the different levels of protection in the defence-in-depth strategy is a key element to avoid the propagation of failure into subsequent levels. In current reactors, an accident can challenge several levels of defence-in-depth simultaneously. In innovative designs, the levels of defence-in-depth should be more independent. This might be accomplished, in part and for some concepts, by more extensive use of inherent safety characteristics and through greater separation of redundant systems. It has the effect of pushing the accident defence to the earlier levels.

An increased use of inherent safety characteristics will strengthen accident prevention in future nuclear installations. A plant has an inherently safe characteristic against a potential hazard if the hazard is rendered physically impossible. An inherent safety characteristic is achieved through the choice of physical and chemical properties of nuclear fuel, coolant and other components. The term inherent safety is normally used with respect to a particular

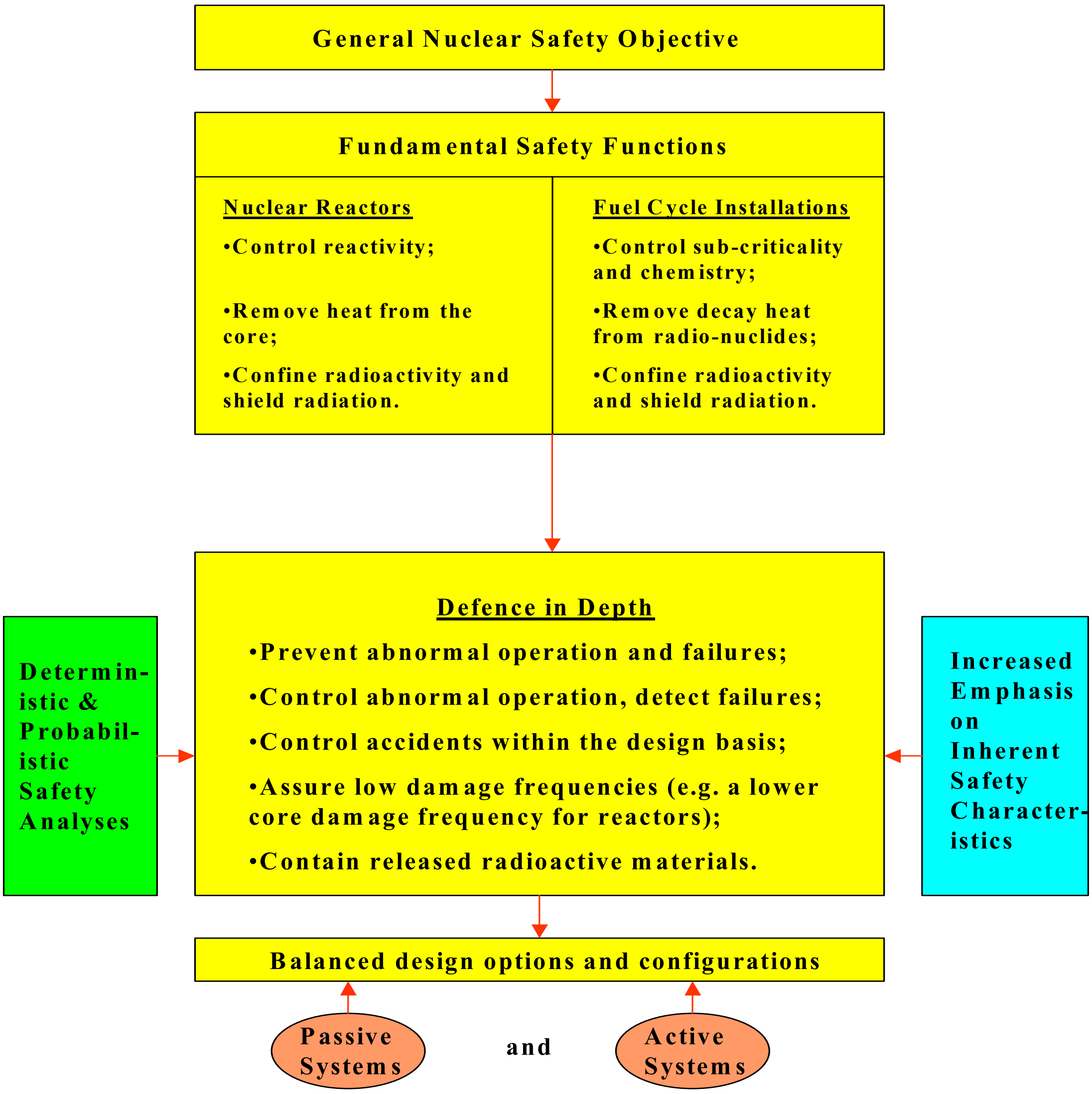


Figure 4.3.1. Approach to development of User Requirements for innovative nuclear energy systems in the area of safety.

characteristic, not to the plant as a whole. For example an area is inherently safe against internal fire if it contains no combustible material; a reactor is partially inherently safe against reactivity insertion if the physically available amount of excess reactivity is small and overall reactivity feedback is negative so that no large power excursions can occur; a reactor is inherently safe against loss of the heat sink if decay heat can be removed by conduction, thermal radiation and natural convection to the environment without fuel damage; a fuel cycle facility is inherently safe against criticality if it cannot contain a critical configuration of material, etc.

The resulting approach to safety of INS is outlined in the Figure 4.3.1.

The general directions for innovation to enhance defence-in-depth are presented in Table 4.3.1.

Table 4.3.1. Innovation direction to enhance the levels of defence-in-depth

Level of defence-in-depth	**Objectives** (see Ref. [4.3-6])	**Innovation Direction (INPRO)**	
1	Prevention of abnormal operation 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 & passive design features; limit fuel failures; increase grace period to several hours.	
4	Control of severe plant conditions, including prevention and mitigation of the consequences 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.	

4.3.2.4. Application of basic safety approach to fuel cycle facilities

Typical safety hazards in fuel cycle facilities include the release of radioactivity, exposures of workers, criticality, releases of chemical, and stored energy (e.g., from radioactive decay, chemical reactions, pressurized systems) [4.3-8]. Techniques and methods similar to those used in current-generation facilities should be used in innovative fuel cycle installations to limit hazards and innovative facilities should benefit from proven technical designs.

Advantage should be taken of inherent characteristics and passive safety systems should be used to the extent possible. But, because manual operations cannot be completely avoided, much emphasis will still need to be put on administrative procedures, including a clear definition of responsibilities and appropriate training for the control of operation.

There is a common agreement that the defence-in-depth strategy should be also used for fuel cycle facilities but defence-in-depth should be applied taking into account the major differences between fuel cycle facilities and reactors, namely:

- The energy potentially released in a criticality accident in a fuel cycle facility is less than that in a reactor power runaway;

- The routine releases may be larger due to mechanical or chemical processes;

- The likelihood of release of chemical energy is higher; and

- The power density is orders of magnitudes less in comparison to a reactor core.

The basic strategy, however, remains the same, namely: all levels of protection should be implemented to keep the whole risk as low as reasonably achievable, social and economic factors taken into account. In addition, dependence on human action in assuring the different levels of defence-in-depth should be reduced.

4.3.3. Basic principles and user requirements

4.3.3.1. Introduction

For innovative reactors and fuel cycle facilities a set of five Basic Principles and twenty-seven User Requirements have been defined. Criteria have also been defined for each of the User Requirements.

The basic principles shall be met by all INS. Most, but not all, user requirements are stated in terms of “should” (desirable but not compulsory) rather than “shall” (compulsory) throughout. This recognizes that the requirements may not be applied in their entirety, because:

- The range of innovative nuclear reactors and fuel cycle installations is so large and their safety characteristics so varied;
- Nuclear power will be a mix of evolutionary, advanced and innovative reactor types so it is not practical that all user requirements and criteria should apply to all types.

The focus is directed to those requirements that would most likely change for innovative nuclear reactors and fuel cycle installations, reflecting the changes in nuclear technology. The concept of ‘Safety culture’ and associated requirements are assumed to be ‘taken over’ from current practice [4.3-9,4.3-10,4.3-11]. It is also assumed that requirements and practices set out in IAEA Safety Standards and Guides will be followed where applicable, e.g., Refs [4.3-1], [4.3-12], [4.3-13]. These provide detailed guidance, e.g., for allowable fuel failure rates and capabilities for resuming operation following a transient.

4.3.3.2. Basic principles

There are five Basic Principles, namely:

Innovative nuclear reactors and fuel cycle installations shall:

1. ***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 from each other than in current installations;***

2. ***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 that of industrial facilities used for similar purposes;***

3. ***Incorporate increased emphasis on inherent safety characteristics and passive safety features as a part of their fundamental safety approach;***

4. ***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;***

5. ***Include a holistic life-cycle analysis encompassing the effect on people and on the environment of the entire integrated fuel cycle.***

This set of basic principles is expected to apply to any type of innovative design. It should foster an appropriate level of safety that can be communicated to and be accepted by Users.

4.3.3.3. User requirements and criteria for all basic principles defined

In the following, for each Basic Principle defined above, the corresponding User Requirements and Criteria are set out in Tables 4.3.2 to 4.3.6.

In Table 4.3.2 the first five user requirements are directed towards a strengthening of the defence-in-depth strategy so that for future nuclear installations – even in the case of severe accidents – evacuation measures outside the plant site are not needed. Safety analyses should cover all modes of operation of the installation to obtain a complete assessment of compliance with defence-in-depth. In the case of simple installations, e.g., related to the fuel cycle, only a deterministic analysis may be needed, as long as defence-in-depth is demonstrated. But for other installations probabilistic analyses should be included.

In Table 4.3.3 the user requirements related to Basic Principle 2 are focused on achieving a very low risk as a result of radiation exposures.

In Table 4.3.4 the user requirements related to Basic Principle 3 are focused on the role of inherent safety in future nuclear designs. These user requirements are complementary to those that are aimed at strengthening defence-in-depth (Table 4.3.1 and 4.3.2).

In Table 4.3.5 the User Requirements related to the RD&D that needs to be performed prior to the deployment of INS are set out.

Table 4.3.2. User requirements and criteria related to Basic Principle 1

Basic Principle 1: *Innovative nuclear reactors and fuel cycle 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 from each other than in current installations.*		
User Requirements	Criteria	
	Indicators	Acceptance Limit
1.1 Innovative nuclear reactors and fuel cycle installations should be more robust relative to existing designs regarding system and component failures as well as operation.	Robustness of design (simplicity, margins).	Superior to existing designs.
	Grace time until human actions are required.	At least one day.
	Inertia to cope with transients.	No material flow out of the primary system.
1.2 Innovative nuclear reactors and fuel cycle installations should detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions and accidents to more serious events.	System variables (e.g., temperature, pressure).	Within operational limits, and safety limits respectively.
1.3 Engineered safety features should be able to restore innovative nuclear reactors and fuel cycle installations to a controlled state, and subsequently (where relevant) to a safe shutdown state, and maintain at least one barrier for the confinement of radioactive material. Reliance on human intervention should be minimal, and should only be required after some grace time.	Probability of occurrence.	$<10^{-2}$ per plant*year (for small breaks). $<10^{-4}$ per plant* year (for large breaks).
	Grace time until human intervention is possible.	At least 30 min (or other regulatory limit).
	Number of barriers maintained.	At least one.
	Degree of sub-criticality at zero power.	Adequate shutdown margin.
	Time required to restore a controlled state without operator actions.	For all facilities appropriately (e.g., <30min for LWRs).
	Degree of sub-criticality at safe shutdown.	Adequate long-term shutdown margin.

Table 4.3.2. User Requirements and Criteria related to Basic Principle 1 (cont.)

Basic Principle 1: *Innovative nuclear reactors and fuel cycle 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 from each other than in current installations (continued).*		
User Requirement	Criteria	
	Indicators	Acceptance Limit
1.4 The frequency of a major release of radioactivity from the fuel in innovative nuclear reactors and fuel cycle installations due to internal events should be reduced.	Frequency of major release of radioactive materials into the containment.	Less than for current new designs; Even lower for installations at urban sites.
1.5 The innovative nuclear reactors and fuel cycle installations shall not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility.	Probability of large release of radioactive materials to the environment.	$<10^{-6}$ per plant*year, or excluded by design.
1.6 A safety analysis shall be performed for innovative nuclear reactors and fuel cycle installations to demonstrate that the different levels of defence-in-depth are met and are more independent from each other than for existing systems. Both deterministic and probabilistic methods should be used, where feasible, to ensure that a thorough and sufficient safety assessment is made. As the technology matures, "Best Estimate (plus Uncertainty Analysis)" approaches are useful to determine the real hazard, especially for limiting severe accidents.	Confidence in the safety analysis methods and in the accident scenarios and postulated hazards.	State-of-the-art methods and tools are used.
1.7 Safe operation of innovative nuclear reactor and fuel cycle installations shall be supported by human factors requirements on the design and construction; by an operating organization committed to safety culture; by ensuring the operating organization has enough knowledge of the plant to be an 'intelligent customer'; and by a social infrastructure that supplies a stable cadre of trained staff.	Evidence that human factors are addressed and a safety culture prevails.	Satisfactory results from periodic assessments, covering technical infrastructure and management areas.

Table 4.3.3. User requirements and criteria related to Basic Principle 2

<table>
<tr><td colspan="4">Basic Principle 2: <i>Innovative nuclear reactors and fuel cycle installations shall 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 that of industrial facilities used for similar purposes</i>.</td></tr>
<tr><td rowspan="5"></td><td rowspan="2">User Requirement</td><td colspan="2">Criteria</td></tr>
<tr><td>Indicators</td><td>Acceptance Limit</td></tr>
<tr><td><i>2.1 Innovative reactors and fuel cycle installations should meet dose limits accepted world-wide as defined by the International Commission on Radiological Protection (ICRP).</i></td><td>Dose value.</td><td>Less than ICRP limits.</td></tr>
<tr><td><i>2.2 The features of innovative nuclear reactors and fuel cycle installations should ensure an efficient implementation of the ALARA Principle through the use of automation, remote maintenance and operational experience from current designs to reduce dose.</i></td><td>Dose values.</td><td>Less than limits defined by national laws.</td></tr>
<tr><td><i>2.3 Dose to an individual member of the public from an innovative nuclear reactor and fuel cycle installation, from normal operation and from accidents, should be reduced below levels from current facilities because of reductions in routine discharges and enhancements to physical barriers.</i></td><td>Dose values.</td><td>Less than limits defined by national laws.</td></tr>
</table>

Table 4.3.4. User Requirements and Criteria related to Basic Principle 3

Basic Principle 3: *Innovative nuclear reactors and fuel cycle installations shall incorporate increased emphasis on inherent safety characteristics as a part of their fundamental safety approach.*			
	User Requirement	Criteria	
		Indicators	Acceptance Limit
	3.1 Innovative nuclear reactors and fuel cycle installations should excel in safety and reliability by incorporating inherently safe characteristics and passive systems into their designs.	Confidence in innovative components and approaches.	Degree of validation.
	3.2 The use of passive systems and inherent safety characteristics in the design of innovative reactors and fuel cycle facilities shall be based on a thorough understanding of all relevant physical and engineering phenomena related to their use, validated by research and demonstration of component behaviour and by all effects system tests.	Knowledge of major phenomena.	In compliance with state-of-the-art.

Table 4.3.5. User requirements and criteria related to Basic Principle 4

Basic Principle 4: *Innovative nuclear reactors and fuel cycle 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.*			
	User Requirement	Criteria	
		Indicators	Acceptance Limit
	4.1 *The safety basis of innovative reactors and fuel cycle installations should be confidently established prior to commercial deployment.*	Transparency of the safety basis.	In compliance with regulatory standards.
	4.2 *The computer codes used to establish the safety of innovative reactor and fuel cycle installations shall be formally verified and validated in their region of applicability.*	Verification/validation of computer codes used.	In compliance with state-of-the-art.
	4.3 *Research, Development and Demonstration on the reliability of components and systems, including passive systems and inherent safety characteristics, should be performed to support the safety assessment.*	Knowledge of major phenomena.	In compliance with state-of-the-art.
	4.4 *A pilot plant or demonstration facility should be built for reactors and/or fuel cycle processes, which represent a major departure from current operating experience.*	Degree of novelty of the process.	*If Needed*: Facility specified, built, operated, and lessons learned documented. *If Not Needed*: Rationale provided.

The User Requirements set out in the table above, related to technical confidence, lead to the need for RD&D, discussed in Section 4.3.4 below. Here, we note that it is common practice to assess the system or component behaviour on the basis of code calculations, operating experience and commonly accepted engineering practice. Uncertainties are taken into account by applying safety margins. For innovative installations, there is no or limited operating experience. Computer codes need to be based on models that have been validated against experimental data, but of necessity this will be to a lesser extent than for existing designs at the early stages of development. In addition to model validation, calculations must be validated against system response tests. Since, such tests are conducted in small scale facilities, it is necessary to adopt appropriate scaling philosophies.

At least the following requirements for the safety basis should be met:

- All significant phenomena, affecting safety, involved in design and operation of a nuclear power plant or a fuel cycle installation have to be understood, modelled and simulated in computer codes (this includes the knowledge of uncertainties, and the effects of scaling and environment); and

- Safety-related system or component behaviour must be modelled with acceptable accuracy, including knowledge of all safety-relevant parameters and phenomena, and validated with a reliable database.

Demonstration of a new technology typically progresses from bench-scale experiments, to small-scale industrial tests, to (possibly) small demonstration or pilot plants, to large-scale prototypes, to full commercialization. The need for a demonstration plant or a prototype plant will depend on the degree of novelty of the process and the potential risk to the owner and the public. Those plants should be able to demonstrate the ability to cope with potential accident initiators.

Whereas for reactors the prevention of large external accidental releases of radioactive material is the major concern, for fuel cycle strategies the reduction of routine *discharges* and the minimization of impacts from wastes are relatively more important. Only a few steps in the nuclear fuel cycle pose significant risks (e.g., at reprocessing plants, high level liquid waste storage facilities and facilities with large stocks of plutonium). Thus, user requirements on innovative fuel cycles should not only address the safety of facilities but also the long-term radiological consequences recognizing that significant progress has already been made in reducing discharges from such facilities [4.3-14].

In the past, nuclear reactor design has led other developments, including fuel. Basic Principle 5 recognizes that for innovative reactors and fuel cycles more integration of development is required, to ensure that releases of radioactive material from all components of the system are considered and optimized for a given concept. Ideally, the impact of the whole reactor and fuel cycle (including the associated waste treatment installations) should be evaluated. A balancing of risks, impacts, and economics should be sought to optimize global energy production. As a consequence, the overall risk associated with INS should be less than that of existing plants. The User Requirements and Criteria set out in Table 4.3.6 provide guidance for such a holistic approach.

Table 4.3.6. User Requirements and Criteria related to Basic Principle 5

<table>
<tr><td colspan="4">Basic Principle 5: <i>Innovative nuclear reactors and fuel cycle facilities shall include a holistic life-cycle analysis encompassing the effect on people and on the environment of the entire integrated fuel cycle</i>.</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">User Requirement</td><td colspan="2">Criteria</td></tr>
<tr><td>Indicators</td><td>Acceptance Limit</td></tr>
<tr><td></td><td>5.1 <i>At the concept definition stage for innovative nuclear reactors and fuel cycle installations, the dose distribution over the entire fuel cycle should be optimized.</i></td><td>Dose distribution.</td><td>Balanced distribution.</td></tr>
<tr><td></td><td rowspan="3">5.2 <i>Mining and Milling for innovative fuel cycles should not bring a disproportionate additional risk to occupational and public health and the environment compared to rest of the fuel cycle.</i></td><td>Occupational radiological exposure.</td><td>In compliance with regulatory limits.</td></tr>
<tr><td></td><td>Expected dose to member of a critical group.</td><td>ALARP[23].</td></tr>
<tr><td></td><td>Expected concentration of radio nuclides and chemical toxins in the environment.</td><td>In compliance with standards of individual member states.</td></tr>
<tr><td></td><td rowspan="4">5.3 <i>Conversion and enrichment of the fuel should not bring a disproportional risk to occupational and public health and the environment compared to the rest of the fuel cycle.</i></td><td>Occupational radioactive exposure.</td><td>In compliance with regulatory limits.</td></tr>
<tr><td></td><td>Expected dose to member of a critical group.</td><td>ALARP.</td></tr>
<tr><td></td><td>Expected concentration of radio nuclides and chemical toxins in the environment</td><td>In compliance with standards of individual member states</td></tr>
<tr><td></td><td>Utilization of Uranium or Thorium.</td><td>Mg of U or Th per GW(e).year (this criterion is included to relate the risk of mining and milling to the overall risk of the fuel cycle).</td></tr>
</table>

---

[23] As Low As Reasonably Practical, social and economic factors taken into account.

Table 4.3.6. User requirements and criteria related to Basic Principle 5 (cont.)

	User Requirement	Criteria	
		Indicators	Acceptance Limit
	5.4 *Spent fuel should be stored avoiding systematic fuel failure and release of radioactive material. In developing innovative fuel designs, proper and safe handling of the fuel in interim storage has to be kept in mind from the beginning (see also Section 4.4.3.1).*	Decay heat removal from spent fuel.	In compliance with regulatory standards.
		Monitoring of fuel behaviour and related documentation.	In compliance with the state-of-the-art.
		Criticality control measures.	In compliance with regulatory limits on sub-criticality.
	5.5 *The safety of advanced reprocessing/ recycling should be superior to the safety of conventional water reactor* UO_2 *reprocessing and U/Pu recycling in thermal reactors.*	Occupational radioactive exposure.	In compliance with regulatory limits.
		Expected dose to member of a critical group.	ALARP.
		Expected concentration of radio nuclides and chemical toxins in the environment.	In compliance with standards of individual member states.
	5.6 *The benefit of reducing the radio-toxicity of wastes arising from innovative fuel cycle technologies by incorporating processes such as partitioning and/or transmutation should be evaluated (see also Section 4.4.3.3).*	Reduction of long-term radio-toxicity (potential radioactive source term.)	To be defined in the future.
		Reduction of decay heat.	To be defined in the future
		Reduction of radioactive waste volume.	To be defined in the future.
	5.7 *Risks to the public due to transportation of innovative fuel cycle materials shall be as low as reasonably practical, social and economic factors taken into account (ALARP).*	Safe transportation of all radioactive materials.	In compliance with regulatory standards.

Table 4.3.6. User Requirements and Criteria related to Basic Principle 5 (cont.)

	User Requirement	Criteria	
		Indicators	Acceptance Limit
	5.8 *The decommissioning strategy for innovative reactor and fuel cycle installations should include technical and administrative means to minimize public and worker radiation exposure. A decommissioning plan should be available at the time of deployment of the installation.*	Are decommissioning plans available to reduce radioactive exposure as well as the quantity and toxicity of the decommissioning waste?	Yes.
		Are the innovative installations designed and will be operated to reduce radiation loads, the amount of toxic waste and to reduce the cost for (future) decommissioning.	Yes.
	5.9 *The response of the installation to a set of credible scenarios should be analyzed for innovative nuclear reactor and fuel cycle installations using deterministic methods.*	Confidence in scenarios and analysis method.	State-of-the-art methods and best available data are used.
	5.10 *To complement the deterministic approach, a probabilistic safety assessment, including the effects of human factors and common cause events, should be performed as part of the design of innovative reactors and fuel cycle installations with a significant hazard potential.*	Confidence in scenarios and analysis method.	State-of-the-art methods and best available data are used.
	5.11 *A risk-informed approach, taking both event frequencies and consequences into account, should be developed further for design optimization and design requirements.*	Application of system rules incorporating risk-informed approaches.	Evidence in compliance.

4.3.4. Required research, development and demonstration

4.3.4.1. Rationale for RD&D

First, a sound knowledge of the phenomena, component, and system behaviour, is required as input to develop computer models for accident analysis. Hence, the more the plant differs from existing designs, the more RD&D is required. Second, RD&D provides the basis for understanding low probability events, so that one can quantify the threats to the integrity of the barriers of the defence-in-depth structure. Finally RD&D can reduce allowances for uncertainties in design, operating envelopes, and in estimates for accident frequencies and consequences.

Successful recruitment of skilled nuclear personnel will depend in part on the attractiveness of the industry and the intellectual challenges it presents, e.g., in innovation. In this respect, safety RD&D will play a role in stimulating the interest of young scientists, engineers and technicians.

4.3.4.2. Safety-related RD&D areas

More research will be needed to bring the knowledge of plant characteristics and the capability of computer codes to model phenomena and system behaviour for innovative nuclear reactors and fuel cycle installations to at least the same confidence level as for existing plants. A recent OECD/NEA workshop on Advanced Nuclear Reactor Safety Issues and Research Needs [4.3-15] will be of particular interest to those involved in planning and designing next generation reactors.

Advanced nuclear power plant designs currently envisioned use, besides light or heavy water (up to supercritical states), liquid metals or gas as working fluids. Their properties in both normal operation and accident conditions must be determined experimentally. It is necessary to carry out further work to better understand various aspects of natural circulation phenomena such as initiation, stability, etc., especially for two phase flow and flow of supercritical fluid.

Neutronic-thermal-hydraulic interaction is another important area that will need further study, mainly for supercritical water and for fluid states like sub-cooled two phase fluid with the potential for coupled neutronic and thermal hydraulic oscillations[24].

For the development of innovative fuel designs, there is a need to look into fuel performance and to consider areas such as dimensional and mechanical stability, possible chemical interaction between fuel element and coolant, and mechanical-chemical interaction between fuel material and fuel element cladding.

A major area of RD&D relates to the transmutation of minor actinides and long-lived fission products in an accelerator driven system (ADS). The spectrum of unresolved problems extends from proton/neutron physics (data base) to thermal-hydraulics of a liquid-metal-cooled system. A similar topic of interest is the use of inert fuel matrices for actinide burning in thermal reactors.

---

[24] e.g., Reactors cooled with supercritical water and BWRs.

Reprocessing is a series of chemical reactions, such as solvent-extraction, oxidation/reduction, electro-refining, ion-exchange, etc. Extensive RD&D in areas as diverse as process control, solvent chemistry, and dry processing (oxidation/reduction reactions) is required. In addition, a method should be developed for quantifying the safety of such facilities.

For innovative systems, digital Instrumentation and Control (I&C) is expected to be used extensively for active control. Again one would expect ‘smarter’ I&C systems, tied to databases representing the current plant state, operating limits (technical specifications), design and PSA models, using artificial intelligence to control the plant, and diagnose and mitigate accidents. Off-site links would help in plant monitoring and problem solving.

Further development of Probabilistic Safety Analyses (PSA) methods, including best estimate plus uncertainty analysis, and their supporting data bases are required and need to be capable of:

- Assessing innovative nuclear designs implemented with lines of defence composed of inherent safety characteristics and passive, as well as active systems;
- Assessing total risk from various states, full power, low power and shutdown, and considering both internal and most external initiating events;
- Accounting for safety culture and human factors;
- Accurately accounting for ageing effects; and
- Quantifying the effects of random, data and modelling uncertainties.

In summary, RD&D activities on innovative reactor and fuel cycle installations are needed to:

- Identify all important phenomena;
- Validate codes in new regimes of fluid and solid material behaviour;
- Justify scaling to commercial size installations;
- Compensate for lack of operating experience;
- Demonstrate the technology at an appropriate scale, e.g., the pilot plant scale; and
- Obtain reliability data.

Thus, RD&D will provide a basis to assess alternative technologies.

Finally, the implementation of defence-in-depth (DID) for advanced reactors including INPRO may require a new approach that would be based on a more advanced interpretation of DID fully integrated with PSA insights. DID has been achieved to date primarily through deterministic analyses based on prevention and/or mitigation. It is expected that risk informed decision-making will play an important role in the development of future reactors and fuel cycle facilities. This will help to achieve high levels of safety while reducing cost, in particular through simplification of safety systems and a sound and well balanced safety classification of safety systems and components. The challenges for the future are to develop more confidence in the PSA tools, to achieve an appropriate integration of deterministic and probabilistic analyses, and to demonstrate that sufficient DID can be achieved through simpler and cheaper technological solutions.

4.3.4.3. Quality assurance of safety RD&D

Quality assurance of data generated in test facilities must be ensured and results have to be documented appropriately so that they are clear and complete enough to be independently reviewed.

4.3.5. Concluding remarks

For innovative nuclear reactors and fuel cycle installations five basic principles have been formulated and twenty-seven user requirements. The approach to safety is based on the application of an enhanced defence-in-depth strategy, supported by increased emphasis on inherent safety characteristics and passive features. Greater independence of the different levels of protection in defence-in-depth from each other is considered a key element to avoid failure propagation from one level to the subsequent one. The end point of the enhanced defence-in-depth strategy is that even in case of severe accidents there will be no need for evacuation of people living nearby the plant, apart from those generic emergency measures developed for any industrial facility.

References to Section 4.3

[4.3-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design Requirements, Safety Standards Series No. NS-R-1, IAEA, Vienna (2000).

[4.3-2] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Basic Safety Principles for Nuclear Power Plants 75-INSAG-3 Rev. 1 INSAG-12, INSAG Series No. 12, IAEA, Vienna (1999).

[4.3-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Advanced Light Water Cooled Reactor Designs – 1996, IAEA-TECDOC-968, Vienna (1997).

[4.3-4] OECD INTERNATIONAL ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL NUCLEAR ENERGY AGENCY, Innovative Nuclear Reactor Development Opportunities for International Cooperation, OECD/IEA, Paris (2002).

[4.3-5] INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety of Nuclear Installations, Safety Series No. 110, IAEA, Vienna (1993).

[4.3-6] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Defence in Depth in Nuclear Safety INSAG-10, INSAG Series No. 10, IAEA, Vienna (1996).

[4.3-7] A. CARNINO, M. GASPARINI, “Defence in Depth and Development of Safety Requirements for Advanced Nuclear Reactors”, Proceedings of an OECD/NEA Workshop on “Advanced Nuclear Safety Issues and Research Needs”, Paris, 18-20 Feb. 2002.

[4.3-8] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of and Regulations for Nuclear Fuel Cycle Facilities, IAEA-TECDOC-1221, Vienna (2001).

[4.3-9] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Safety Culture (A Report by the International Nuclear Safety Advisory Group), INSAG Series No. 4, (Safety Series 75), IAEA, Vienna (1991).

[4.3-10] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Management of Operational Safety in Nuclear Power Plants INSAG-13, INSAG Series No. 13, IAEA, Vienna (1999).

[4.3-11] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Key practical Issues in Strengthening Safety Culture INSAG-15 (Including Booklet), INSAG Series No. 15, IAEA, Vienna (2002).

[4.3-12] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment and Verification for Nuclear Power Plants Safety Guide Safety Series No. NS-G-1.2, IAEA, Vienna (2002).

[4.3-13] INTERNATIONAL ATOMIC ENERGY AGENCY, Accident Analysis for Nuclear Power Plants, Safety Reports Series No. 23, IAEA, Vienna (2002).

[4.3-14] ALLAN, C.J., ALLSOP, P.J., ANDERSON, R.W., BOSS, C.R., and FROST, S.E., "Radioactive Releases in the Nuclear Fuel Cycle – Recent Experience and Improvements", Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities Contributed Papers, IAEA-TECDOC-990, IAEA, Vienna (1997).

[4.3-15] OECD NUCLEAR ENERGY AGENCY, INTENATIONAL ATOMIC ENERGY AGENCY, Proceedings of NEA/IAEA Workshop on Advanced Nuclear Reactor Safety Issues and Research Needs, Paris, 18-20 February 2002, OECD/NEA, Paris (2002).

4.4. Waste management

4.4.1. Introduction

4.4.1.1. Purpose and objectives

According to the IAEA [4.4-1] "...radioactive waste may be defined as material that contains, or is contaminated with, radionuclides at concentrations or activities greater than clearance levels as established by the regulatory body, and for which no use is foreseen."

In Section 4.4 we:

1. Specify and discuss basic principles and user requirements for safe management of radioactive waste in an innovative nuclear energy system, and
2. Recommend research and development that would improve the management of radioactive waste in innovative nuclear energy systems.

4.4.1.2. Relationship to sustainability

To be sustainable nuclear energy systems must be managed in such a way that future generations are not unduly burdened, either with adverse effects of the waste or with having to look after the waste. The adverse effects that the various components of the radioactive waste may have on the environment must be prevented or mitigated effectively to make nuclear energy sustainable in the long term. Moreover, improvements brought about by INS should include improvements in the safe management of radioactive wastes. In fact, to be successful, any innovative technology must emphasize long-term waste management to a degree consistent with its importance to society. Sustainability related aspects of the problem are discussed in detail in Section 4.2 of this report.

4.4.2. Basic principles

As noted in Section 4.3.2.1, the overall objective of nuclear safety is to protect individuals, society, and the environment from harm by establishing and maintaining effective defences against radiological hazards from nuclear installations. This section addresses requirements for safety of radioactive waste management for innovative reactors and fuel cycles.

The IAEA [4.4-1] has issued a set of principles for radioactive waste management, which are adopted as the Basic Principles for the safety of waste by INPRO. The overall objective of waste management is to deal with radioactive waste management in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations. These principles are as follows:

1. ***Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.***
2. ***Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.***
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.***
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.***

5. ***Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.***
6. ***Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.***
7. ***Generation of radioactive waste shall be kept to a minimum practicable.***
8. ***Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.***
9. ***The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.***

It is with reference to these Basic Principles that the user requirements for radioactive waste management for INPRO have been defined.

4.4.3. User requirements

4.4.3.1. Pre-disposal waste management

Intermediate steps between generation of the waste and the end state should be taken as early as reasonably practicable. The design of the steps should ensure that all-important technical issues (e.g., heat removal, criticality control, confinement of radioactive material) are addressed. The processes should not inhibit or complicate the achievement of the end state.

Rationale

By definition, the state of the waste that provides permanent safety is the end state. Other states of the waste that occur during operation of the fuel cycle are considered intermediate states leading to the end state. The waste must be put in its end state by steps. Leaving these steps to future generations without compensating justification would fail to meet the 5th Basic Principle that radioactive waste shall be managed in such a way that will not impose undue burdens on future generations. The steps should not complicate the achievement of the end state. Care should be taken for each step of waste management not to bring the waste into a form that is incompatible with planned subsequent steps. Furthermore, waste should not be put into a form that would increase the difficulty of attaining the waste form planned for the end state. According to Basic Principles 1 and 2 and 9 the safety of each process and activity (including transportation), under normal and accidental conditions should be considered and all technical issues important for safety (e.g., removal of heat from the systems, storage in a sub-critical condition, properly confining the radioactive materials) should be addressed.

Time to reach the end state

Competing factors affect how soon the waste is brought to its end state. Early processing could preclude the use of superior future technology. Delaying processing and final disposition could result in substantial near-term cost savings but far greater weight must be given to the decrease in uncertainty and increase in safety that will result from early achievement of an appropriate end state. The past practice, in some areas, of keeping high-level radioactive waste in liquid form not appropriate in the long term, has led to a legacy of large amounts of such waste, which must now be subject to remediation at great cost to the present generation and which could lead to significant accidental releases to the environment, as has happened on some occasions in the past. With the increase in the use of nuclear power it will become increasingly vital that waste be brought to a proper end state early. Retaining waste in forms and under conditions that are not permanently safe entails a risk that the waste will never be put in such a state. The prescription "as early as reasonably practicable" places significant weight on avoiding unnecessary delay.

Processing needed to bring the waste to its final form

Processing operations are part of the overall fuel cycle and their environmental and health effects need to be considered and justified by the net benefits that would be achieved by the processing step. The ability to produce the waste form and package on a commercial scale should be evident, either through demonstration or confirmed design, before the energy system is implemented to assure that the innovative fuel cycle would not generate waste for which the required end state is not feasible.

Safety of processes and activities

All technical issues for the safety of all processes and activities under normal and accidental conditions must be taken into account and properly addressed. Such issues are strongly technology dependent and may change from one waste management strategy to another. For some processes, removal of decay heat may be required, in others, prevention of criticality may be an issue, or, in the transport of radioactive waste between two different processes, design of special casks might be required.

Compatibility of processes

The form of the radioactive waste at the end of a process step must be compatible with the next step, so effort must be made to ensure this in a large complex system. Design of the waste management system throughout the energy system and throughout the life cycle of each of its components must be seen as an integrated whole. Nothing should inhibit or complicate the achievement of the end state

4.4.3.2. End state

For each waste in the energy system, a permanently safe, achievable 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.

Rationale and approach

This requirement relates to Basic Principles 1, 2, 4, 5, and 9. The end state is to protect people and the environment today from any harmful effects of the waste and to protect people and the environment in the future to at least the same level that is acceptable today. The definition of each end state should include: the waste form and package; the final repository containing the waste packages; a safety case for the final repository; and a schedule for achieving the end state.

The waste form and package

Ideally, the waste form and package should be designed to retain radioactive materials until they have decayed to levels that meet the requirements for free release. In cases where this is not practicable other features of the waste management system must be relied upon. The suitability of the waste form and package must be proven in relation to the environmental conditions that they will be subjected to in the waste management scheme.

The final repository containing the waste packages

Ultimately, the longer-lived components of waste will have to be put in a final waste form, packaged and the packages placed in some form of repository. The integrated system will have to be demonstrated to be permanently safe according to then current regulatory standards. The greatest emphasis today in national programs is to rely on underground repositories. The designs and operation of these facilities vary, e.g., in the depth at which packages are emplaced, the host geological medium chosen, and the period of monitoring prior to sealing and closure of the repository.

Low- and intermediate-level waste packages are isolated in relatively near surface repositories in many States. The protective features include the waste packages, sealing materials in the repository, as well as the natural barriers to movement of material through the geological environment. Most advanced nuclear power countries are planning to dispose of spent fuel and/or high-level waste in deeper repositories in stable geological media. Although progress is being made (see also Section 2.2.4), it has proven difficult to site and license such a repository, so no repository for this waste is yet in operation and interim storage is used.

Long-term safety of the final repositories could be improved by partitioning and transmutation (P&T) involving the irradiation of long-lived radioisotopes to transform them into stable or short-lived elements. This could significantly reduce the total amount of long-lived radioactive material requiring final disposal. Although the technology would require further development, it has the potential to significantly improve the long-term safety of radioactive waste from the fuel cycle.

A safety case

A safety case is defined as the sum total of all evidence (quantitative and qualitative) that supports the determination that the waste management system will be acceptably safe. A minimum requirement is the determination that all applicable laws and regulations will be satisfied. The defined end state must be permanently safe in the sense that future generations will not be exposed to risk that is not acceptable today. In general, the end state should be shown to provide effective protection until decay processes render its potential effects below the level suitable for free release. The safety case will need to include an analysis of any risks related to failure of institutional controls. It is expected that the safety case will be more easily made for those end states that are based on passive safety, i.e., where long-term institutional controls are not necessary for safety. If long-term institutional controls are necessary for safety, such as in the case of perpetual storage, the risk associated with potential failure of these controls should be accounted for in the safety case.

4.4.3.3. Adverse effects on human health

Waste management systems should be designed to assure that their associated adverse radiological and non-radiological effects on humans are below the levels acceptable today. Because the 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.

The Requirement relates to Basic Principles 1 and 4. To assure an adequate margin of safety in consideration of uncertainties and to incorporate the spirit of continuous improvement, the energy systems should be designed with a view to the radiological effects being below the levels acceptable today. Notwithstanding the possibility that low levels of radiation are less harmful to human health than currently reflected in regulatory policies, the precautionary principle dictates that the design of radiological protection err on the side of safety.

Optimization of the waste management system designs should be viewed in the context of optimization of the complete energy system, as put forward in Section 4.2. Thus, the optimization of any single component is secondary. The factors to be considered include:

- Radiotoxicity, as a function of time, of the wastes generated;
- Ability of the waste form to retain radionuclides under normal and accident conditions;
- Mobility of the toxic elements through environmental pathways;
- The time over which long-lived radionuclides remain in interim storage;
- The degree to which the wastes are kept in a passively safe state, and
- Occupational exposure in waste management facilities.

As an illustration, P&T of components of spent fuel are considered. The radiotoxicity of spent fuel decreases as the result of radioactive decay. The long-term radiotoxicity is due primarily to actinides and a small number of fission products (FPs) with very long half-lives. Transmutation of these long-lived nuclides into shorter-lived nuclides would reduce the long-term radiotoxicity of the material. However, such transmutation would require processing of the spent fuel, which would make the toxic elements more mobile. In addition, the quantity of actinides and long-lived FPs on or near the surface may be increased for a long time as they are processed, stored, and cycled to reactors or accelerator-driven systems. Passive safety of storage systems could be affected by the different chemical and physical nature of the materials containing the actinides and the long-lived FPs. Finally, additional occupational exposure may occur. Thus, the evaluation of the effectiveness of partitioning and transmutation requires a careful assessment of several competing factors.

If nuclear power were to take a significantly increased share of the world's energy production, it is likely that reprocessing of the used fuel would be necessary. Such reprocessing would mobilize the actinides and long-lived FPs as well, whether or not they are subjected to transmutation processes. Thus, the evaluation of whether or not to transmute actinides and long-lived FPs would be quite different if one considers that reprocessing is required as part of the fuel cycle.

It is not likely that all parts of an energy system with radiological consequences will be contained within the jurisdiction of a single State. Nevertheless, the radiological safety of one part of the system should not be viewed in isolation. It is the overall impact of the energy system that should be optimized.

4.4.3.4. Adverse effects on the environment

Waste management strategies should be such that the 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.

Rationale and approach

Basic Principle 2 states that radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment. All parts of the energy system should be considered in an integrated manner to be consistent with the requirements set out in Section 4.2, and the complete life cycle of each component of each facility should be considered (cradle to grave). Cumulative effects over time and space, without regard to national boundaries, should be considered to avoid the generation of unacceptably large effects by the accumulation of smaller ones. Non-radiological stressors arising from the management of the radioactive waste should also be taken into account. The first priority is to avoid the generation of the waste or the generation of a particular problem radionuclide or compound. The second priority is to improve the processing and treatment of wastes.

Waste strategies to minimize the hazard from radioactive waste should be implemented in all parts of the energy system including: methods of mining and milling; fuel types; reactors; reprocessing and recycling (this sometimes includes P&T steps); and waste treatment.

Methods of mining and milling

Uranium mining and milling is accompanied by release of some of the radioactive progeny into environment and this is responsible for the long-term radiological hazard of the tailings. Methods to separate the important nuclides (^{230}Th, ^{226}Ra, ^{231}Pa) should be considered in designing mining and milling processes for INPRO energy systems.

Fuel types

Some of the fuel types for advanced cycles are listed below.

- *ThO_2 fuel*: Thorium, an abundant fertile material is used to produce the fissile isotope ^{233}U, which is recycled. The production of Pu and other actinides is reduced. However, new radionuclides, such as ^{231}Pa, not existing in the U–Pu cycle, are generated.
- *DUPIC fuel*: Spent PWR fuel is fabricated into PHWR fuel without aqueous processing minimizing the generation of HLW and reducing mining and milling wastes. Fuel radiotoxicity can be reduced by burning actinides in the PHWR.
- *U–Pu nitride fuel*: This fuel type is being investigated in Russia. The spent nitride fuel can be regenerated by non-aqueous technology with less liquid waste and P&T of long-lived radionuclides.

Reactors

All aspects of reactor design and operation should be reviewed to identify possibilities for reducing the volumes of wastes. Improvement in efficiency of the energy conversion process could reduce the waste produced per unit of energy to the end user. Improvement in the utilization of mined U and Th by the reactor could reduce the impacts of mines and mills.

Decontamination by improved methods should be used more often. For example, activated metals can be partly decontaminated by melting to take advantage of the differentiated behaviour of fission products (FP) and actinides in the melt. Segregation of waste streams from different areas of the reactor can be used to avoid cross-contamination of the waste.

Reprocessing and recycling

Reprocessing and recycling may or may not include P&T of the actinides and long-lived FPs. If so, the long-lived radionuclides would be partitioned from HLW, some of which would be transmuted while others could be used or separately disposed of. If transmutation were not used, the separated long-lived actinides could be immobilized in a tailored ceramic which may have advantages over vitrification.

Waste treatment

Intermediate waste management steps should ensure that waste packages fulfil the waste acceptance criteria of the final, permanently safe end state. Secondary wastes and gaseous or liquid emissions from waste treatment facilities should be considered when evaluating waste conditioning methods.

The most desirable approach for reducing waste is to do so at the source (Section 4.4.3.5); however, there are limitations on how much reduction at source is possible while still operating effectively and economically. The waste that is produced can be treated to reduce the volume requiring disposal. Such reduction is already achieved in many facilities using current technologies, including:

- Compaction, super compaction, incineration, sintering and melting (for solids);
- Chemical precipitation, evaporation, ion exchange and membrane separation (for liquids);
- Thermal solidification of liquid concentrates (bituminisation, vitrification, drying).

New technologies for volume reduction are also being investigated such as:

- Cold crucible melting and plasma melting; and
- Non-flame technologies such as steam reforming, electron beam, UV photo-oxidation and supercritical waste oxidation.

4.4.3.5. *Reduction of waste at the source*

The energy system should be designed to minimize the generation of wastes and particularly wastes containing long-lived toxic components that would be mobile in a repository environment.

Basic Principle 7 states that the generation of radioactive waste shall be kept to a minimum practicable. Reduction of waste production at the source is a preferred method consistent with the objectives of INPRO and is potentially of even greater importance if production of nuclear energy increases.

The design stage offers the greatest potential for reducing waste as it offers the maximum flexibility to adjust the characteristics of the system for this purpose. The minimization of waste by design is an important aspect of inherently safer designs. Components of the waste that are toxic for a long time and that are mobile in the repository environment are particularly important targets for reduction.

Methods for reducing the generation of radioactive waste include:

- Segregation of waste streams to avoid cross contamination and to increase the proportion of waste suitable for controlled or free release and to decrease the volume of material that represents a long-term hazard;

- Recycling and reuse of materials that would otherwise be radioactive waste;
- Optimizing the design to facilitate decommissioning and dismantlement of facilities;
- Extraction of long-lived decay products in mining and milling operations; and
- Reduction of secondary wastes from waste management systems.

Technologies worthy of consideration for further development include:

- Use of non-aqueous methods of processing spent fuel;
- Improvement of existing aqueous methods of processing spent fuel;
- P&T of long-lived radionuclides in power reactors or accelerator driven systems;
- Application of advanced materials, such as cobalt-free steels, to reduce activation;
- Improved fuel cycle efficiency;
- Improved efficiency of the energy conversion process at reactors; and
- Improved decontamination technology.

4.4.3.6. Attribution of waste management costs

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.

Basic Principle 5 states that radioactive waste shall be managed so as not to impose undue burdens on future generations. Thus, they should be provided with the means to maintain the waste in a safe condition. The responsibility for providing these resources, including funds and proven technology, rests with those who have benefited from the generation of the waste and the associated costs should be included in the estimated cost of energy. The internalisation of all costs is a fundamental requirement of sound environmental management.

In principle, the assets accumulated to manage the wastes should cover the accumulated liability. This is contrary to the common practice of “under-funding” the present liability and planning on the future value of money to compensate. Such a practice fails to properly internalise the cost associated with waste production. More importantly, the practice provides a built-in incentive to delay processing and safe disposal of the waste. Some common sense judgment will have to be used to target a reasonable period after start-up of the energy system in which to balance the assets and liabilities, because, otherwise, the liability associated with the first small generation of waste would be prohibitive. The cost of any long-term institutional controls would have to be included in the estimated cost of waste management.

4.4.4. User requirements and criteria

Criteria are listed in Tables 4.4.1 to 4.4.6 associated with User Requirements set out above.

Table 4.4.1. User requirement 1 (Pre-disposal waste management) and criteria for safety of waste management

User Requirement	Criteria	
	Indicators	Acceptance Limit
1. Pre-disposal Waste Management: *Intermediate steps between generation of the waste and the end state should be taken as early as reasonably practicable. The design of the steps should ensure that all important technical issues (e.g., heat removal, criticality control, confinement of radioactive material) are addressed. The processes should not inhibit or complicate the achievement of the end state.*	Time to produce the waste form specified for the end state.	As short as reasonably practicable.
	Technical indicators: e.g., ● Criticality compliance. ● Heat removal provisions. ● Radioactive emission control measures. ● Shielding specifications. ● Volume/activity reduction measures. ● Radiotoxicity.	Criteria as prescribed by regulatory bodies of specific Member States.
	Process descriptions that encompass the entire waste life cycle.	Complete chain of processes from generation to final end state and sufficiently detailed to make evident the feasibility of all steps.

Table 4.4.2. User requirement 2 (end state) and criteria for safety of waste management

User Requirement	Criteria	
	Indicators	Acceptance Limit
2. End State: *For each waste in the energy system, a permanently safe, achievable 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.*	Technological achievability of the end state.	All required technology currently available[25] or reasonably expected to be available on a schedule compatible with the schedule for introducing the proposed innovative fuel cycle. Any time required to bring the technology to the industrial scale must be less than the time specified to achieve the end state.
	Practical achievability of the end state (Sustainability issue).	Resources (space, capacity, etc.) available for achieving the end state compatible with the size and growth rate of the energy system.
	Safety of the end state (long-term expected dose to an individual of the critical group).	The current ICRP recommendations should be satisfied.
	Time to reach the end state.	As short as reasonably practicable.

---

[25] The word "currently" is used in this document to refer to the time at which the acceptability of a nuclear energy system is being evaluated. The criterion is explicitly intended to allow innovative methods of waste management, such as partitioning and transmutation or advanced waste forms, to be investigated.

Table 4.4.3. User requirement 3 (adverse effects on human health) and criteria for safety of waste management

User Requirement	Criteria	
	Indicators	Acceptance Limit
3. Adverse Effects on Human Health: *Waste management systems should be designed to assure that their associated adverse radiological and non-radiological effects on humans are below the levels acceptable today. Because the 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.*	Estimated dose rate to an individual of the critical group.	Follows current ICRP recommendations.
	Estimated concentrations of chemical toxins in the environment.	Meet standards of specific Member State.
	Radiological exposure of workers in activities involving the management of waste.	Meets regulatory standards of specific Member State.

Table 4.4.4. User requirement 4 (adverse effects on the environment) and criteria for safety of waste management

User Requirement	Criteria	
	Indicators	Acceptance Limit
4. Adverse Effects on the Environment: *Waste management strategies should be such that the 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.*	Estimated concentrations of radionuclides and chemical toxins in the environment.	Meet standards of specific Member State.
	Exposures of sensitive species to these expected concentrations.	Would not be expected, on a scientific basis, to cause adverse effects at the population level.
	Other environmental indicators.	Meet requirements as specified in Task 4.2 of INPRO.

Table 4.4.5. User requirement 5 (reduction of waste at the source) and criteria for safety of waste management

User Requirement	Criteria	
	Indicators	Acceptance Limit
5.Reduction of Waste at the Source: *The energy system should be designed to minimize the generation of wastes and particularly wastes containing long-lived toxic components that would be mobile in a repository environment.*	Alpha-emitters and other long-lived radionuclides.	ALARP.
	Total activity.	ALARP.
	Mass.	ALARP.
	Volume.	ALARP.
	Chemically toxic elements that would become part of the radioactive waste.	ALARP.
	Radiotoxicity.	ALARP.

Table 4.4.6. User requirement 6 (attribution of waste management costs) and criteria for safety of waste management

User Requirement	Criterion	
	Indicator	Acceptance Limit
6. Attribution of Waste Management Costs: *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.*	Specific line item in the cost estimate.	Included.

4.4.5. Recommended research and development

The adverse effects of radioactive waste in INS can potentially be reduced by RD&D on relevant technologies. Table 4.4.7 summarizes recommended areas that offer particularly good potential for reducing these adverse effects. Detailed information is available in Working Materials prepared during INPRO Phase 1A.

Table 4.4.7. Recommended research

RD&D	Objectives	Expected time for results
Methods of characterizing wastes in the nuclear fuel cycle.	Reduce occupational exposure and improve efficiency. Facilitate showing compliance with waste acceptance criteria.	Short.
Waste treatment methods.	Reduce radiological impact from storage and disposal of wastes. Decrease the amount of hazardous material requiring disposal.	Medium.
Reprocessing of spent fuel.	Improve waste stream characteristics. Reduce secondary wastes.	Medium to Long.
Interim Storage Methods.	Increase safety of interim storage.	Short to Medium.
Partitioning and Transmutation.	Reduce long-lived radioactive components in HLW. Enhance the efficiency of partitioning operations.	Medium to Long.
Geological Disposal.	Demonstrate disposal technologies. Improve geological characterization. Enhance understanding of hydro-geochemical transport processes. Improve long-term monitoring technologies. Facilitate the detailed design of geological repositories.	Medium.
Long term human factors analysis.	Assess risks associated with waste management systems that require long-term institutional controls.	Short.
Design-based comparisons of waste arising from proposed advanced reactors and fuel cycles.	Incorporate safety of waste management and fuel reprocessing in the fuel cycle evaluations.	Short.

4.4.6. Concluding remarks

Nine Basic Principles, developed by the IAEA, govern the safety of radioactive waste management within INPRO. Arising from these Basic Principles INPRO defined six User Requirements providing guidance for developers of innovative energy systems.

For each of these User Requirements, Criteria have been specified. The safety of radioactive waste management for innovative systems can benefit from RD&D in areas such as methods of waste characterization, waste treatment methods, spent fuel reprocessing, partitioning and transmutation, geological disposal, long term human factors, and design-based comparisons of wastes arising from proposed innovative reactors and fuel cycles.

Reference to Section 4.4

[4.4-1] INTERNATIONAL ATOMIC ENERGY AGENCY, TITLE, Safety Series No. 111-F, IAEA, Vienna (1995).

4.5. Proliferation resistance

4.5.1. Introduction

In designing future nuclear energy systems, it is important to consider the potential for misuse of such systems for the purpose of producing nuclear weapons. Such considerations are among the key considerations behind the international non-proliferation regime, with its many national and multinational agreements and institutions, and the IAEA safeguards system is a fundamental element of this regime. For States with safeguards agreements and additional protocols in force, the Agency aims to provide assurance not only regarding the non-diversion of nuclear material for weapons purposes, but also of the absence of undeclared nuclear material and activities. However, even for such States, the safeguards system can only provide strong assurances with the full cooperation and transparency of a State. Moreover, it is important to bear in mind that the cost of providing safeguards assurances depends on the nature of the nuclear energy system used in a State. Should nuclear power based on existing technologies greatly expand, detecting the diversion of civilian nuclear material or the misuse of facilities dedicated to the peaceful use of nuclear energy or undeclared nuclear materials or nuclear activities will become increasingly costly.

The purpose of this chapter is to provide guidance to government, sponsors, designers, regulators, investors and users of nuclear power on the incorporation of proliferation resistance in future nuclear energy systems, and to facilitate public understanding of future proliferation resistance and its role in the international non-proliferation regime.

In October 2002, an international technical meeting, held in Como, Italy, convened by the IAEA reached consensus on a definition of terminologies such as proliferation resistance, intrinsic features and extrinsic measures. The meeting also discussed proliferation resistance fundamentals for future INS. A large part of this chapter is based on the international consensus reached at the meeting.

Definitions

Proliferation Resistance is defined as that characteristic of a nuclear energy system that 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.

The degree of proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures. These can be classified as *intrinsic features* and *extrinsic measures*.

In the context of this report, proliferation resistance is limited to proliferation by states and does not include protection against the theft of fissile materials by sub-national groups or the sabotage of nuclear installations or transport systems.

Intrinsic proliferation resistance features are those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures.

Extrinsic proliferation resistance measures are those measures that result from States' decisions and undertakings related to nuclear energy systems.

Safeguards is 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 alias, on site inspections. This term has different meaning depending on context. In this report, "**safeguards**" will refer to IAEA safeguards implemented under Safeguards Agreements between a State and the IAEA. "**Regional safeguards**" will be used to refer to a regime of independent international verification of commitments made by States within Regional Agreements such as the Euratom Treaty or the Guadalajara Declaration[26]. "**National safeguards**" will be used to refer to a State System of Accounting and Control, along with physical protection.

4.5.2. Intrinsic features

Four general types of intrinsic features have been identified. It is expected that the design groups responsible for new nuclear energy systems will examine these and identify specific features applicable to their nuclear energy system that will accomplish the intended objectives of each. A comprehensive assessment of the robustness of the proliferation resistance measures should be undertaken to determine the degree of proliferation resistance provided by the intrinsic features. Such an assessment would guide the application of extrinsic measures necessary to supplement the intrinsic features.

It is important to recognize that although these features can make a significant contribution to proliferation resistance of a nuclear energy system, they do not, in themselves, make a nuclear energy system completely proliferation resistant.

The first type of intrinsic proliferation resistance feature consists of the technical features of a nuclear energy system that reduce the attractiveness for nuclear weapons programmes of nuclear material during production, use, transport, storage and disposal. These include material characteristics such as isotopic content, chemical form, bulk and mass, and radiation properties. These features affect the difficulty in converting the material into a form suitable for use in a weapon.

The second type of intrinsic proliferation resistance feature comprises the technical features of a nuclear energy system that prevent or inhibit the diversion of nuclear material. These include design features that confine nuclear material to locations with limited points of access, and material that is difficult to move without being detected due to such characteristics as size, weight, or radiation.

The third type of intrinsic proliferation resistance feature consists of the technical features of a nuclear energy system that prevent or inhibit the undeclared production of direct-use material. This includes 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; fuel cycle facilities and processes that are difficult to modify for undeclared production of nuclear material; and processes with intrinsic limitations that would preclude their use for production of direct-use material.

The fourth type of intrinsic proliferation resistance feature consists of the technical features of a nuclear energy system that facilitate verification, including continuity of knowledge. This includes designs that facilitate design information verification throughout their life cycles,

---

[26] Agreement between the Republic of Argentina and the Federative Republic of Brazil for Exclusively Peaceful Use of Nuclear Energy based upon INFCIRC/395 [4.5-1].

design features that facilitate nuclear material accounting and verification, and design features that provide for the installation of surveillance, monitoring and sealing equipment where these are likely to be required for verification. This fourth type of intrinsic feature facilitates efficient and cost-effective safeguards.

4.5.3. Extrinsic features

Extrinsic proliferation resistance measures result from States' decisions and undertakings related to nuclear energy systems and can be divided into five categories. The first are States' commitments, obligations and policies with regard to nuclear non-proliferation and disarmament. These include the Treaty on the Non-Proliferation of Nuclear Weapons (the NPT) and nuclear-weapons-free zone treaties, comprehensive IAEA safeguards agreements[27] and protocols additional to such agreements.[28]

The second category consists of agreements between exporting and importing States that nuclear energy systems will be used only for agreed purposes and subject to agreed limitations. This category includes such things as: arrangements for supply and return of nuclear fuel or other components of a nuclear energy system, agreements governing the re-export of nuclear energy system components by an importer, and guarantees by a nuclear energy system exporter of reliable and favourably priced supplies of fresh fuel (reducing the need of the importer to develop indigenous enrichment technologies) and waste management services over the life-cycle of the nuclear energy system (reducing the need of the importer to develop indigenous reprocessing technologies).

The third category consists of commercial, legal or institutional arrangements that control access to nuclear material and nuclear energy systems. Arrangements made to ensure that operators of nuclear energy systems are subject to specific requirements governing the use of those systems and associated materials, and multi-national ownership, management and control of nuclear energy systems would fall into this category.

The fourth category of extrinsic measures is application of IAEA verification and, as appropriate, regional, bilateral and national measures, to ensure that States and facility operators comply with non-proliferation or peaceful-use undertakings (i.e. safeguards).

The fifth consists of legal and institutional arrangements to address violations of nuclear non-proliferation or peaceful-use undertakings.

4.5.4. Basic principles

Five basic principles provide high-level guidance regarding INS (see Table 4.5.1).

4.5.5. User requirements

Five top-level user requirements provide guidance regarding INS (see Table 4.5.2). This list of user requirements is not intended to be complete or exhaustive, but to provide high-level guidance.

---

[27] Comprehensive IAEA safeguards agreements are based upon INFCIRC/153 [4.5-2].

[28] Additional Protocols are based upon INFCIRC/540 [4.5-3].

Table 4.5.1. Basic principles for proliferation resistance

1	***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.***
2	***Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself.***
3	***Extrinsic proliferation resistance measures, such as control and verification measures will remain essential, whatever the level of effectiveness of intrinsic features.***
4	***From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged.***
5	***Communication between stakeholders will be facilitated by clear, documented and transparent methodologies for comparison or evaluation/assessment of proliferation resistance.***

Table 4.5.2. User Requirements for proliferation resistance

1	*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.*
2	*Future nuclear energy systems should incorporate complementary and redundant proliferation resistance features and measures that provide defence in depth.*
3	*The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized to provide cost-effective proliferation resistance.*
4	*Proliferation resistance should be taken into account as early as possible in the design and development of a nuclear energy system.*
5	*Effective intrinsic proliferation resistance features should be utilized to facilitate the efficient application of extrinsic measures.*

The first requirement encourages consideration of how proliferation resistance features and measures will ensure that future nuclear energy systems continue to be an unattractive means to acquire nuclear material for a nuclear weapons program. These considerations must anticipate potential increases in nuclear power, increased use of nuclear materials suitable for the manufacture of nuclear weapons, increased size and complexity of nuclear material processing facilities, and the corresponding costs and potential challenges to maintaining safeguards effectiveness.

Developers are encouraged to consider intrinsic features to support proliferation resistance in their designs, and governments are encouraged to consider extrinsic measures to supplement the intrinsic features, in order to maintain or improve upon the level of proliferation resistance provided by today's nuclear energy systems.

The second requirement acknowledges that use of appropriately chosen redundant and complementary design features for proliferation resistance can result in strengthened proliferation resistance through defence in depth. Defence in depth is accepted and practiced in areas such as safety and security, providing enhanced assurance that goals are met and systems are robust. This concept will provide similar benefits in the area of proliferation resistance but requires careful selection of complementary and redundant features and measures that offer high benefit at low cost.

The third requirement recognizes that cost-effective proliferation resistance is achieved through use of optimal combinations of intrinsic features and extrinsic measures. Complete reliance on extrinsic measures results in high costs for verification. On the other hand, there may be a point at which the cost to add another intrinsic feature to enhance proliferation resistance in a design exceeds the benefit (i.e. the point of diminishing returns). This requirement acknowledges that there are trade offs between different intrinsic features and extrinsic measures, as well as tradeoffs between intrinsic features for proliferation resistance and other design considerations such as safety, maintainability and cost.

The fourth requirement encourages designers to consider proliferation resistance from the early stages of design. This provides the greatest opportunity to incorporate intrinsic design features with minimal additional cost. For example, consideration of proliferation resistance could result in small changes to the layout of the nuclear energy system and have little impact on cost. The first generation of nuclear energy systems was deployed with less consideration of proliferation resistance. It is now widely recognized that some design features affect the cost of safeguards and therefore, under the strengthened IAEA safeguards measures, parties to IAEA safeguards requirements are obligated to begin consultations with the IAEA on the manner in which safeguards will be employed as soon as the decision is made to construct a nuclear installation (i.e. the IAEA provides guidance on design measures to facilitate the application of safeguards at future water-cooled reactors in IAEA report STR-392, [4.5-4]).

The fifth requirement acknowledges that the inclusion of effective intrinsic features will increase the efficiency of extrinsic measures (e.g., safeguards) that are required. The requirement does not encourage inclusion of as many intrinsic features as possible, but rather of the effective ones that provide significant benefits to the extrinsic measures. The third and fifth requirements are closely related, in promoting an optimal combination of effective intrinsic features and efficient extrinsic measures to provide efficiency and cost effectiveness.

4.5.6. Indicators and criteria

The INPRO definition of *Nuclear Energy System* includes the full spectrum of facilities in a fuel cycle and associated institutional measures. INPRO assessments include consideration of both technical features and institutional measures, and a means to combine these considerations. Most past assessments in the area of proliferation resistance have focused on technical features of the facilities, and have not considered institutional measures. Synthesis of proliferation resistance evaluations of facilities and institutional measures is a significant challenge.

Criteria, consisting of indicators and limits, for each user requirement are tabulated below. Discussion of the indicators and limits is provided after Tables 4.5.3–4.5.7.

Table 4.5.3. User requirement 1 and criteria for proliferation resistance

User Requirements	Criteria	
	Indicator	Acceptance Limit
1. 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.	1.1 First level indicator: Confidence that the proliferation resistance features and measures that are implemented in the design, construction and operation of future nuclear energy systems to help ensure that the INS is an unattractive means to acquire fissile material for a nuclear weapons programme.	An acceptable rating on a qualitative scale ranging from unacceptable to outstanding.
	1.1.1 Second level indicators accounting for intrinsic features and extrinsic measures are listed below. • States' commitments, obligations and policies regarding non-proliferation and disarmament. • Attractiveness of nuclear material for a nuclear weapons programme. • Prevention or inhibition of the diversion of nuclear material. • Prevention or inhibition of the undeclared production of direct-use material.	For each of the second level indicators, an acceptable rating on a qualitative scale ranging from unacceptable to outstanding, computed from third level indicators using an appropriate method (e.g., attribute analysis, scenario analysis).

Table 4.5.3. User Requirement 1 and Criteria for proliferation resistance (cont.)

1. 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.	1.1.2 Examples of third level indicators are listed below. (The list is not intended to be comprehensive and some third level indicators may not be applicable to some INS's). Examples of extrinsic measures that are third level indicators [4.5-4]: • Safeguards agreements pursuant to the NPT. • Export control policies. • Relevant international conventions. • Commercial, Legal or institutional arrangements that control access to nuclear material and nuclear energy systems. • Bilateral arrangements for supply and return of nuclear fuel. • Bilateral agreements governing re-export of nuclear energy system components. • Multi-national ownership, management or control of a nuclear energy system. • Verification activities. • State or regional systems for accounting and control. • Safeguards approaches for the nuclear energy system, capable of detecting diversion or undeclared production. • An effective international response mechanism for violations. Examples of intrinsic features that are third level indicators [4.5-4. 4.5-5] : • Isotopic content of nuclear material. • Chemical form of nuclear material. • Radiation field from nuclear material. • Heat generated by nuclear material. • Spontaneous neutron generation rate from nuclear material • Complexity of, and time required for modifications necessary to use a civilian INS for a weapons production facility. • Mass and bulk of nuclear material. • Skills Expertise and Knowledge required to divert or produce nuclear material and convert it to weapons useable form. • Time required to divert or produce nuclear material and convert it to weapons useable form. • Design features that limit access to nuclear material.	Third level indicators are inputs for the evaluation of the second level indicators and do not generally have individual acceptance limits. Proliferation resistance is provided through appropriate combinations of these elements. Examples of extrinsic measures are extracted from IAEA STR-332 [4.5-4]. Examples of intrinsic features are extracted from an annex to the NERAC Task Force Report on Technology Opportunities for Increasing the proliferation resistance of Global Civilian Nuclear Power Systems (TOPS) [4.5-6]. Further detail and discussion on these indicators can be found in those reports.

Table 4.5.4. User requirement 2 and criteria for proliferation resistance

User Requirement	Criteria	
	Indicator	Acceptance Limit
2. Future nuclear energy systems should incorporate complementary and redundant proliferation resistance features and measures that provide defence in depth.	2.1 First level indicator: Confidence that a INS makes effective use of redundant and complementary features and measures to achieve defence in depth.	An acceptable rating on a qualitative scale ranging from unacceptable to outstanding.
	2.1.1 Second level indicators.	
	• Number of barriers comprising intrinsic features and extrinsic measures.	• At least X barriers; X to be determined by the body making the assessment.
	• Robustness of each barrier.	An acceptable rating on a qualitative scale ranging from unacceptable to outstanding.
	• Redundancy or complementarity within intrinsic features.	• At least Y intrinsic features; Y to be determined by the body making the assessment.
	• Redundancy or complementarity within extrinsic measures (e.g., dual containment and surveillance).	• At least Z extrinsic measures; Z to be determined by the body making the assessment.
	• Assessment of system strength and weakness to ensure that all potential vulnerabilities are covered by intrinsic features, extrinsic measures and combinations thereof.	An acceptable rating on a qualitative scale ranging from unacceptable to outstanding.

Table 4.5.5. User requirement 3 and criteria for proliferation resistance

User Requirement	Criteria	
	Indicator	Acceptance Limit
3. The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized to provide cost-effective proliferation resistance.	3.1 Cost for incorporating intrinsic features and applying extrinsic measures required to provide adequate proliferation resistance.	Minimal Cost (understanding that an acceptable level of proliferation resistance is required by User Requirement 1).

Table 4.5.6. User requirement 4 and criteria for proliferation resistance

Requirements	Criteria	
	Indicator	Acceptance Limit
4. *Proliferation resistance should be taken into account as early as possible in the design and development of a nuclear energy system.*	4.1 Consideration of proliferation resistance in all major decisions made by the responsible bodies regarding a INS, including design concepts, R&D, demonstration facilities, finance, licensing, sales, export, construction, operation, decommissioning, etc.	Proliferation resistance is taken into account in all major decisions made by the responsible bodies regarding a INS, including design concepts, R&D, demonstration facilities, finance, licensing, sales, export, construction, operation, decommissioning, etc.
	4.2 The stage in the development/design for the INS at which proliferation resistance is considered in the process. Illustrative initial steps are outlined below.	
	• Early consideration may be done by the developer and must involve personnel with sufficient understanding of PR.	• Concept Design Stage.
	• The stage at which the governments involved in the INS deployment and licensing aspects have to set up or implement a legislative or regulatory framework.	• As soon as there is a firm plan for deployment.
	• The stage at which verification agencies develop preliminary safeguards approaches.	• As soon as sufficient technical information is available and where there is a firm plan for deployment.

Table 4.5.7. User requirement 5 and criteria for proliferation resistance

Requirements	Criteria	
	Indicator	Acceptance Limit
5. *Effective intrinsic proliferation resistance features should be utilized to facilitate the efficient application of extrinsic measures*.	5.1 Awareness of extrinsic measures by designers.	Potential extrinsic measures to be used are made known to the designers.
	5.2 Extent to which intrinsic proliferation resistance features are used in the verification approach.	Intrinsic proliferation resistance features are used to the extent possible in the verification approach.
	5.3 Safeguards approach with a reasonable level of extrinsic measures.	Agreement between IAEA or other verification authorities and State on a safeguards approach.

4.5.6.1. Indicators for user requirement 1

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.

Indicators for this requirement facilitate assessment of how well the intrinsic features and extrinsic measures make an INS proliferation resistant. The process for such assessment is not currently defined and will necessarily have to be based on a clear, documented, transparent, internationally accepted method. Such an assessment is the subject of current development by several national and international groups.

Assessments need to bep conducted and updated throughout the life cycle of the INS, beginning with assessment of the concept as soon as sufficient technical information is available, continuing through the design process to guide designers to include effective intrinsic features, and into the decommissioning phase. These assessments must consider the facilities and institutional measures associated with the full INS including mining, refining, enrichment, energy production, reprocessing, waste storage, and final disposal. Assessments need to be reviewed periodically to account for changes. For example, if means were found to separate plutonium in a civilian spent fuel pyro-processing facility, then the proliferation resistance of this technology would need to be re-assessed. Also new or better indicators may be identified and should be considered.

The way to achieve confidence that an INS is an unattractive means to acquire fissile material, is through evaluation of a number of second level indicators. These represent potential barriers to proliferation. Four, second level indicators are identified:

- States' commitments, obligations and policies regarding non-proliferation and disarmament;
- Attractiveness of nuclear material for a nuclear weapons programme;
- Prevention or inhibition of the diversion of nuclear material; and
- Prevention or inhibition of the undeclared production of direct-use material.

These indicators encompass both intrinsic features and extrinsic measures. For example, diversion may be inhibited by, *inter alia*, the mass/bulk of items being diverted, radiation fields, the location of the material, the verification measures that are in place, and contractual arrangements for fuel supply and return. These second level indicators recognize that undeclared production could be conducted within a civilian INS, or misuse of civilian technology to construct an undeclared facility for production.

Evaluation and synthesis of second level indicators requires consideration of a wide range of details. These details, or third level indicators, are factors to consider in assessing proliferation resistance. Individually, they are not indicators that a system is proliferation resistant or an unattractive means to acquire fissile material. At this level of detail, indicators may be of different relevance depending on, *inter alia*, the specific portion of the fuel cycle being examined, characteristics of the facilities and the application of the INS. Examples of third level indicators are listed in Table 4.5.3.

Identification, evaluation and synthesis of the evaluations of individual third level indicators must be done in accordance with a clear, documented, transparent and internationally accepted proliferation resistance assessment method.

4.5.6.2. Indicators for User Requirement 2

Future nuclear energy systems should incorporate complementary and redundant proliferation resistance features and measures that provide defence in depth.

Indicators for this user requirement are measures that assess the degree to which a future INS makes effective use of complementary and redundant features and measures to provide defence in depth.

Defence in depth is incremental and one can always increase proliferation resistance by adding another effective layer of defence. The intent of this user requirement is to promote complementary and redundant features and measures only where they significantly strengthen proliferation resistance by providing supporting lines of defence against proliferation at an acceptable cost. Redundant features and measures that do not significantly contribute to defence in depth, but that increase the cost to design, construct, operate, or decommission the INS should be avoided. This is also relevant to UR3.

An indicator for this UR needs to be more than a count of the number of redundant and complementary, features and measures. Assessment is required to (1) identify the complementary and redundant features and measures, (2) determine the strength of each feature and measure, and (3) determine the extent to which they contribute to the overall defence in depth for the INS. The latter step considers both layering and balance; multiple layers of defence against one acquisition path do not provide true defence in depth if other acquisition paths are left undefended; moreover, a system that achieves proliferation resistance through a few good features and measures may be far more proliferation resistant than a INS that achieves its proliferation resistance through a multitude of features and measures.

Redundant features and measures provide increased reliability. Complementary features and measures provide additional barriers or layers of defence. Defence in depth can be strengthened both by a combination of complementary intrinsic features and extrinsic measures, as well as by a combination of complementary intrinsic features and a combination of complementary extrinsic measures. These concepts are reflected in the second level criteria for this user requirement.

4.5.6.3. Indicators for User Requirement 3

The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized to provide cost-effective proliferation resistance.

The indicator for this user requirement is cost. For comparative purposes, evaluation of this indicator should be normalized to output produced (e.g., cost per kilowatt-hr thermal, cost per kilowatt-hour of electricity, cost per litre of desalinated water, or cost per m^3 of hydrogen).

Assessment of this indicator will require development of ways to account for the full scope of costs. These must include, *inter alia*, costs for:

- All lifecycle costs from cradle to grave, and all steps from mining to final disposal;

- Incremental engineering, construction, operating, decommissioning, and disposal costs to include intrinsic features in the design;

- Costs associated with implementing other extrinsic measures that are specific to the particular INS (e.g., incremental overhead to operate a multi-national fuel supply centre versus a state-owned fuel supply centre);

- Verification equipment (e.g., installed and portable equipment used for inspections); and

- Independent verification (e.g., IAEA and regional safeguards inspections).

Some costs will be a challenge to assess. The second point addresses design choices for a INS that are made to enhance its proliferation resistance and result in additional costs. Many design choices are made for multiple purposes and it will be challenging to assess the degree to which some design choices were made to enhance proliferation resistance. Some design choices are clearly made to enhance proliferation resistance, particularly those that are specifically intended to facilitate safeguards (e.g., special access provisions for reverification of spent fuel in dry storage modules or signal cable penetrations for safeguards equipment).

The criterion for evaluating this user requirement is not intended to preclude the addition of low cost intrinsic features that strengthen the proliferation resistance of an INS beyond the minimum acceptable level. Such additional intrinsic features may be beneficial for achieving public acceptance, marketing, government policy, or other objectives.

4.5.6.4. Indicators for User Requirement 4

Proliferation resistance should be taken into account as early as possible in the design and development of a nuclear energy system.

Recognizing the benefits of taking proliferation resistance into account early in the development of an INS, the first indicator is consideration of proliferation resistance in all major decisions. This indicator recognizes the importance of considering proliferation resistance in a wide range of decisions including not only design, engineering, construction, operation and decommissioning decisions, but also in decisions regarding licensing, sales, and export.

The second indicator is the stage at which proliferation resistance is considered. This is not limited to the design process. Illustrative initial steps pertaining to design, deployment, licensing and verification are outlined.

The developer should consider proliferation resistance as soon as sufficient technical information is available in the development of a new INS. This should be no later than the conceptual design stage and could begin earlier as fundamental design concepts are discussed. Early consideration provides opportunity for the design to be guided, in part, by proliferation resistance, before significant design decisions are finalized.

Governments should consider proliferation resistance as soon as there is a firm plan for deployment of an INS. This provides opportunity to develop deployment strategies, as well as legislative and regulatory frameworks that strengthen the proliferation resistance of the INS.

Verification agencies should develop preliminary verification approaches as soon as there is a firm plan for deployment and sufficient technical information is available. This preliminary approach may evolve as additional design details become available. Early consideration provides useful feedback to the developers and allows the development of efficient verification approaches.

4.5.6.5. Indicators for User Requirement 5

Effective intrinsic proliferation resistance features should be utilized to facilitate the efficient application of extrinsic measures.

The distinguishing aspect of this user requirement is that it encourages use of effective intrinsic features to facilitate the application of extrinsic measures.

The first criteria for this user requirement, is that potential extrinsic measures be made known to the designers of the INS. Designers require this knowledge to identify effective intrinsic features that would have an impact on extrinsic measures.

The second indicator is that intrinsic proliferation features are used, to the extent possible, in the verification approach. Evaluation to determine that this condition is met involves examination of the verification approach and the design features of the INS.

The third criterion for this user requirement is agreement between the IAEA and State on a safeguards approach for the INS, or all elements thereof. Where applicable, this would also include agreement with other verification agencies and the State on the verification approach. Verification is a key extrinsic measure that can be significantly affected by intrinsic features.

4.5.7. Assessment of proliferation resistance

Application of the requirements presented in Section 5 requires an accepted means to assess the proliferation resistance of a nuclear energy system. Such assessments would serve a number of diverse uses. In addition to facilitating clear communication, such assessments could be used by designers to assess the impact of intrinsic design features on the overall proliferation resistance of their system. This would allow designers to make informed choices and to incrementally improve the proliferation resistance of a design. An assessment method could also be useful by verification regimes to assess the effect of verification (extrinsic measures) on the proliferation resistance of a nuclear energy system. This could be used to tune extrinsic verification measures to provide effective and cost-effective proliferation resistance for a nuclear energy system. Finally, an assessment method could be used in making such decisions as the selection of competing nuclear energy options for research, development and deployment; selection of alternative nuclear energy systems for export or import; and setting export policies for nuclear products.

It is widely recognized that a common assessment method needs to be developed that will allow such determinations to be made in a consistent manner. The proliferation resistance assessment method will likely be a composite incorporating scenario-based and attribute-based tools used in reliability analysis and adapted to this purpose.

Scenario-based approaches consider proliferation, diversion or acquisition paths. Analysis involves modelling the processes undertaken by an adversary to overcome the barriers to proliferation, and estimating the likelihood of success in achieving a proliferation objective. These approaches often use logic modelling techniques and methods commonly applied in probabilistic safety assessment. The results are quantitative but use structured, subjective judgements of experts as inputs.

Attribute analysis examines proliferation barriers such as the characteristics of the fuel and the design features of the systems. Each attribute is weighted based on expert judgement and assessed. This form of analysis tends to be more qualitative than scenario-based analysis, and often makes use of formal methods from decision theory such as multi-attribute utility theory.

Assessments of proliferation resistance are required at a number of levels. Structured judgments based on checklists (a form of attribute analysis) can be useful to developers and planners. Such assessments confirm whether or not specific points have been considered or addressed, but may not provide sufficient information for comparative or semi-quantitative purposes.

Qualitative assessments, whether based on scenario or attribute analysis, are more complex than checklists and are useful for such purposes as assisting a developer in making design decisions about intrinsic features, or assessing the adequacy of the proliferation resistance features of a facility.

Quantitative assessments, where they can be provided and are accepted, provide transparent, structured, detailed assessments that can be peer reviewed. When used to compare different INS, care is required to assess the full mix of nuclear facilities including fuel cycle facilities, and different types of reactors. In some cases synergies may make a mix of two different types of reactors considerably more proliferation resistant than when the individual reactors are considered separately.

In order to promote international acceptance, the theoretical foundation for any proliferation assessment method should be based on methods that are used in assessments of issues of comparable complexity. The resultant method should be transparent and easy to understand. Parameters and methods for assigning values to parameters should be described and justified. In order to be effective and applied correctly, an assessment method must be supported by user-friendly computer tools suitable for use by a wide range of analysts.

Because assessment of proliferation resistance is a difficult and complex task, it is likely that the initial versions may be contentious and complicated, but that an accepted method will evolve through use and successive critiques. It is critical that any methodological limitations be clearly identified to avoid misinterpretation or misapplication.

4.5.8. Research and development

Concentrated efforts are required to develop specific technological features and institutional arrangements that will allow the goals established for proliferation resistance to be realized. Certain aspects of this work will necessarily be undertaken within the design efforts for new nuclear energy systems. Other aspects might be explored on more general terms, including new technical measures to facilitate verification, and new institutional arrangements to guarantee that the benefits sought will be realized if implemented.

The mechanism for co-ordinating such research and development remains to be established.

References to Section 4.5

[4.5-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Agreement Between The Republic Of Argentina And The Federative Republic Of Brazil For The Exclusively Peaceful Use Of Nuclear Energy, INFCIRC/395, IAEA, Vienna (1992).

[4.5-2] INTERNATIONAL ATOMIC ENERGY AGENCY, The Structure And Content of Agreements Between The Agency And States Required In Connection With The Treaty On The Non-Proliferation Of Nuclear Weapons , INFCIRC/153 (Corrected), IAEA, Vienna (1972).

[4.5-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Model Protocol Additional To The Agreement(s) Between State(s) And The International Atomic Energy Agency For The Application Of Safeguards, INFCIRC/540 (Corrected), IAEA, Vienna (1997).

[4.5-4] INTERNATIONAL ATOMIC ENERGY AGENCY DEPARTMENT OF SAFEGUARDS, Proliferation Resistance Fundamentals for Future Nuclear Energy Systems, STR-332, IAEA, Vienna (2002).

[4.5-5] UNITED STATES DEPARTMENT OF ENERGY NUCLEAR ENERGY RESEARCH ADVISORY COMMITTEE, Annex, Attributes of Proliferation Resistance for Civilian Nuclear Power Systems, NERAC, (http://www.doe.ne.gov) (2000).

[4.5-6] UNITED STATES DEPARTMENT OF ENERGY NUCLEAR ENERGY RESEARCH ADVISORY COMMITTEE, Technological Opportunities To Increase The Proliferation Resistance Of Global Civilian Nuclear Power Systems (Tops), Report by the Tops Task Force of the Nuclear Energy Research Advisory Committee, NERAC, (http://www.doe.ne.gov) (2001).

4.6. Cross cutting issues

4.6.1. Introduction

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 relate to infrastructure – national, regional, and international. This chapter discusses a number of such infrastructure issues taking into account the different scenarios discussed in Section 4.1.1 and indicates possible developments and conditions that would facilitate the deployment of INS.

It is recognized that nuclear energy systems need to fit the circumstances of countries and markets in which nuclear power is needed. For example, the future deployment of innovative reactors in countries that have only a limited national nuclear infrastructure could be facilitated if the INS were owned and operated by an international nuclear utility or if they were inherently safe and delivered as a “black box – nuclear battery”. A number of non-technical issues would need to be addressed and arrangements developed, possibly, for example, international or regional regulatory regimes and organizations, for this to become a reality. Those countries that develop nuclear technology can be expected to continue to operate and maintain substantial nuclear infrastructure. In such countries, standardization of requirements and regulations could facilitate cost reductions by enabling greater economies of scale to be realized. One general condition to be satisfied for wider utilization of innovative nuclear power in the future is that of public acceptance which plays an ever more important role in decision-making processes.

Factors that need to be considered when opting for nuclear power are extensively described in earlier publications of IAEA. See, for example, Refs [4.6-1] and [4.6-2]. In this chapter emphasis is put on developments that could facilitate the deployment of innovative nuclear concepts in the light of expected changes in world circumstances.

4.6.2. Nuclear power infrastructure

4.6.2.1. Overview

The nuclear power infrastructure may be defined to be all features or 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. In this section some of the main features that comprise current nuclear power infrastructures will be highlighted. In subsequent sections the infrastructure needs for the deployment of innovative nuclear power reactors and fuel cycles in the future will be examined in the light of possible changing world circumstances.

One factor affecting the existing nuclear power infrastructure in many countries is that of government ownership of electricity production and distribution systems and the linkage between nuclear power and national industrial development strategies. This is changing, gradually in some countries and more rapidly in others, with the private-sector market-economy assuming a greater role while that of governments decreases.

The scenarios discussed in Section 4.1.1 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 modify infrastructures, both nationally and regionally, and to do so in a way that will facilitate the deployment of nuclear power systems in developing countries.

Changes in market structures provide opportunities for enhanced cooperation among countries to take best advantage of such changes. The emphasis on national infrastructure could be expected to diminish as regional or international elements of the necessary infrastructure are developed. This is expected to be most important to countries with a relative modest need for nuclear capacities or to countries with limited industrial capacity, since the investment they would have to make in developing their national infrastructure would be considerably diminished.

The results of any review of infrastructure trends in the longer term can only be of an indicative character and point to the direction to be taken to facilitate the deployment of innovative nuclear concepts. Regional differences will still be expected to be a factor, the importance of which will depend on whether the world moves more towards global co-operation or towards regional co-operation.

In the following sections of this chapter infrastructure trends and developments are discussed in more detail within three categories: legal and institutional infrastructure, economic and industrial infrastructure, and socio–political infrastructure.

4.6.2.2. Legal and institutional infrastructure

Establishment of a nuclear power program entails legal requirements at both the national and international level. These requirements give rise to the need to establish a legal framework that provides the basis for establishing safety requirements and for the control and oversight of operations and of security arrangements, including non-proliferation, as well as other conditions that have to be fulfilled. Responsibility for development of the legal framework rests with national governments and implementation of the legal framework involves national organizations and institutions, in particular in the areas of policy, regulation and RD&D. National standards for safety comply with internationally agreed standards and guidelines and international conventions on the safety of nuclear installations and waste management (see Refs cited in [4.6-1] and [4.6-2] and page 7 of Ref. [4.6-3]) have been ratified by a majority of countries that are using nuclear power.

An important part of the legal structure is the regulation of liabilities. In this area, as in safety, international cooperation has lead to international conventions that set out the main principles on responsibilities for liabilities (see pages 36 to 39 of Ref. [4.6-1]). A majority of countries that make use of nuclear energy subscribe to these conventions although there is no international agreed obligation to do so.

As well, there is extensive co-operation among member states of the IAEA to control the proliferation of the non-peaceful use of nuclear technology, resulting in safeguards regimes and agreements on non-proliferation (see pages 39 to 41 of Ref. [4.6-1]).

As stated above, the legal framework that governs the application of nuclear technology in general and nuclear power in particular is the responsibility of national governments and is set out in national legislation. Although international guidelines and conventions [4.6-1] provide general guidance for such national legislation, there are many differences among countries. To be licensed, a nuclear reactor has to comply with national requirements, as set out in national regulations. A licence obtained in one country is not automatically applicable in other countries, albeit that countries contracting to a vendor for the supply of a reactor often require that the reactor be licensable in the country of origin.

Taken as a whole, the legal framework and associated institutional structures have a distinctive character that establishes nuclear technology as special and apart from the regulatory framework of other industries, reflecting the special nature of the risks that are seen to be associated with nuclear technology. This is not likely to change until there is a greater acceptance of these risks. This, in turn, may depend on a reduction of those risks and especially of the consequences of accidents that can potentially lead to large releases of radioactive materials.

Two main developments could affect the existing legal structures with beneficial effects. In the first place, the development of innovative reactors to comply with the Basic Principles, Requirements and Criteria set out in earlier sections of Chapter 4 could make it possible to change the way the production of nuclear energy is regulated. When, for example, the financial and safety risk 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 changed and simplified. So, as innovative energy systems that meet the INPRO Principles and Requirements are realized, the existing legal structures for operating nuclear systems could and should be re-evaluated.

Secondly, globalization and internationalization of the markets for energy as well as for energy equipment could influence the existing legal structures governing the deployment of nuclear energy. 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. Establishing a harmonized licensing system (or, alternatively, reaching agreements that national licences are accepted internationally) requires an international agreement on the basis for licensing. Agreement already exists to some extent and is reflected in international conventions, standards, and guides but enhanced international cooperation will be necessary to achieve the degree of harmonization that should be possible. National governments have a duty to assure the safety of their populations. It can be anticipated that governments will become more amenable to accepting international regulations and procedures as the risks and potential adverse effects of nuclear power are diminished.

The process of harmonization could well start by cooperation among individual supplier countries and among countries that do not have a domestic industrial capability for the development of nuclear energy systems. It is expected that suppliers, investors and international operators of nuclear energy systems would find it advantageous to agree to a licensing mechanism whereby once a given nuclear energy system had been licensed, on the basis of meeting agreed regulations, standards and requirements, that the licence would be valid in any country where the system might be deployed. Such a development would also seem to be advantageous to MS in which the system would be used. Conditions for the realisation of such developments include the absence of trade barriers that impede such international co-operation and acceptance by national regulators.

Since the development of national legal structures and the technical competence required to utilize these structures effectively requires a major effort, it would make sense for countries that are interested in acquiring nuclear energy to co-operate with like-minded countries, perhaps regionally, and so share the cost of developing the necessary infrastructure. Such regional co-operation could be even more advantageous as responsibility for energy supply moves from the public sector to national or international private-sector companies.

The process of licensing nuclear facilities, providing independent oversight, and enforcing the conditions and obligations required by the licence, requires a competent nuclear regulatory authority with sufficient knowledge to fulfil its duties and responsibilities. The expected growth of demand for energy is foreseen to be largely in developing countries and amongst them countries that do not have a highly developed nuclear knowledge base and infrastructure. In such countries, regional or international licensing and regulatory mechanisms and organizations could play an important role.

To take full advantage of changing market-structures liability arrangements also have to be considered. These arrangements are very specific for nuclear technologies with residual liabilities resting with the host country. It is expected that international companies will play a growing role in the supply of electricity on international markets from nuclear power plants. This calls into question the current arrangements regarding liabilities in the event of an accident. Reducing the risk attributed to nuclear power could facilitate changes in liability arrangements that can be expected to be sought.

Conditions that could facilitate the deployment of innovative nuclear technology can be summarized as follows:

- Changes in legal and institutional structures can be considered as innovation leads to changes in the properties and performance of future nuclear energy systems;
- To take advantage of the globalization and internationalization of the demand for nuclear energy and of the supply of both nuclear energy and of INS, countries should cooperate in establishing more generally applicable licensing mechanisms and regulations;
- Enhanced cooperation among countries will be facilitated by international and regional agreements on the basic principles, requirements, and related standards that should be applied to siting and operating nuclear energy systems and which would form the basis for cooperation on establishing a general licensing system;
- To diminish the burden for the development of national institutions necessary to control the application of nuclear energy systems regional or international arrangements and institutions could be developed; and
- The growth of international operating companies would be facilitated by ensuring that the insurability of risk attributed to the production of nuclear power can be handled in the same way as other industrial risks. Once it has been shown that innovative technology has made this possible, the actual arrangements governing liabilities would need to be reviewed.

4.6.2.3. Economic and industrial infrastructure

Many factors must be taken into account when determining whether nuclear power can be deployed successfully in a given country. These include factors related to the physical infrastructure, such as the compatibility of the electrical grid with the unit size, the ability to transport the heavy equipment, etc. But other factors also come into play such as the ability to arrange financing and the availability of qualified construction contractors. Of course, a functioning electricity market and an adequate price for the electricity supplied are also prerequisites The IAEA has published several studies on the factors that have to be considered by countries when choosing the nuclear power option, particularly developing countries. See for example Refs [4.6-1] and [4.6-2] and the references cited therein. In INPRO, emphasis is put on developments and conditions that could facilitate the deployments of INS taking into account the various scenarios discussed in Chapter 2 and Section 4.1.

Whether or not implementation of nuclear power in a given country succeeds reflects, in most cases, the economic conditions in that country. Industrial infrastructure varies from country to country. Countries that developed indigenous nuclear energy technology were generally industrialized and were capable of manufacturing components and constructing the nuclear power stations. Countries that imported nuclear energy technology from vendor countries have often seen the adoption of nuclear power as a part of their further industrialization and economic growth.

There are no firm requirements regarding the industrial support infrastructure needed for starting a nuclear power program. But, within the country, the plants have to be built, equipment and components have to be installed and commissioned, and the finished plants have to be operated and maintained. This translates into a requirement, at some stage, for an industrial support infrastructure to supply materials, components and services. Such capabilities are often acquired via technology transfer agreements with vendors.

Once the plant is built it must be supplied with fuel. The nuclear fuel cycle consists of a number of distinct industrial activities, which can be separated into the front end, comprising those steps prior to fuel irradiation in the plant, and the back end, including the management of the spent fuel. Today, utilities are, in many cases, purchasing fuel on the international market, thus taking advantage of international enrichment and fuel fabrications capabilities. Using the international market for fuel supply has proven to be reliable and it is normally cheaper. For the final disposal of the waste, however, it is common that countries have to put in place their own facilities within their national boundaries. The availability of disposal facilities that can accept waste from a variety of countries [4.6-4], particularly from those countries that operate a small nuclear energy system, could facilitate the deployment of nuclear energy systems. In a world characterized by globalization and internationalization the development of innovative energy concepts would involve international co-operation and shared development efforts and RD&D (e.g., the CRP's of IAEA and GIF initiative). Enhanced cooperation in the field of enabling technologies and the use of advanced developments from other industries could contribute to sustainability.

As the demand for electricity is expected to grow mainly in developing countries particular attention should be paid to the infrastructure in these countries. For countries that need only a small number of nuclear power plants it may not be cost effective to develop a fully capable domestic supply structure. In such countries, international operating companies that can bring most of the necessary infrastructure for building, owning and operating nuclear power systems, would supply a valuable service. If, through mechanisms such as this, and with innovative designs better matched to the needs of developing countries, the challenge of establishing and supporting the required national infrastructure could be substantially reduced.

A driving force for innovation in nuclear power technology is the demand for sustainable energy. Each component in the overall system has to fulfil this global requirement. Optimizing individual components, however, probably does not result in the optimal overall system. The complete fuel cycle, including the use of various reactor types and including the handling of waste should be optimized as a system. Such a systems approach cannot be applied in isolation within each individual country with a need for nuclear power, but must be developed within a global or regional international context. This requires enhanced cooperation among countries that apply nuclear power systems. In the future, international operating companies could assume a growing role in realizing such an approach.

Security of energy supply in a country or region has always played an important role in choosing among energy options. As INS become available that meet the needs of developing countries nuclear energy will be an attractive option for improving security of energy supply in such countries [4.6-5, 4.6-6].

In summary, the following conditions would be expected to favour the deployment of INS:

- Optimization of the overall nuclear energy system will be fostered when component facilities located in different countries are viewed as part of an international multi-component system. Such optimization would help innovative energy systems contribute to sustainable development;
- Market demands and the specific needs of different markets need to be recognized by technology developers, particularly the needs of developing countries that have a limited infrastructure and a real but limited need for nuclear energy;
- Companies involved in research, development and supply of nuclear technology can facilitate the deployment of INS when they supply a full-scope service, up to and including the provisions of management and operations; and
- Innovative nuclear energy systems will be better positioned to contribute to the security of supply in developing countries when their specific needs are taken into account.

4.6.2.4. Socio-political infrastructure

Public acceptance

Public acceptance of nuclear power technology is generally seen as a key condition for the successful deployment of additional nuclear capacity. As public acceptance issues vary from country to country and particularly between developed and developing countries, there is no general “one-size-fits-all” approach for dealing with this issue. As discussed in Section 2.2, in a minority of countries public opposition has stopped the building of new nuclear plants and led, in some countries, to plans for the phasing out of operational nuclear power plants, including even in countries that are, themselves, suppliers of nuclear power plants. On the other hand, several of the major countries are expanding or planning to expand their nuclear capacity and are maintaining extensive RD&D programs. Despite these differences there seems to be a number of common issues that are important to the question of public acceptance.

The development of INS needs to address, to the extent possible, such issues of general concern. These include the risk of a serious reactor accident with the potential for wide spread contamination, even beyond national boundaries since, in the past, accidents with nuclear technology have influenced public acceptance not only in the country where the accident has occurred but much more widely. Other issues include the claim that the used fuel and waste from reprocessing represents a problem that has no solution and the alleged close link between civilian nuclear power and nuclear weapons. As discussed in Sections 4.3 to 4.5, INPRO has developed Basic Principles, User Requirements and Criteria for innovative reactors and fuel cycles in each of these areas, as well as in the area of sustainability and environment, Section 4.2. Thus, such innovative systems are addressing the issues of public acceptance head on. But these innovative concepts have yet to be demonstrated. International cooperation could be instrumental in furthering such demonstrations.

One area where international co-operation can contribute is that of the application of standards. It is of the greatest importance to apply the highest standards of safety to nuclear projects and operations. Differences among countries in the main standards and in safety culture dealing with safety, waste management, environmental protection, and proliferation resistance could negatively influence the public acceptance of nuclear power. Agreement on and application of the highest applicable standards in each country can contribute to a wider acceptance of nuclear power. Ways need to be found to facilitate their application by making available the necessary technology and knowledge to developing countries that do not have the means to develop such standards themselves.

Another factor is related to the life cycle of nuclear power investments, including design, construction, operation, decommissioning, and the waste management, that may well extend over fifty years in most cases and can easily extend beyond one hundred years. Thus, the firm long-term commitment of the government and other stakeholders, e.g., through adequate legal structures and regulatory commitments, 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 [4.6-3].

Human resources and knowledge preservation

The development and use of nuclear power technology requires adequate human resources and knowledge. There is already concern about the availability of sufficient capacity to operate and support the existing fleet of nuclear power plants. So, focused efforts have to be made to ensure that human resources are available to first bring about and then capitalize on the innovative developments that are the subject of INPRO. While this may be a daunting task, 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. Companies operating on a global base can develop specialist teams that provide services to plants in many different countries. At the same time, the design of INS should seek to reduce the demand for skilled manpower for plant operations and routine maintenance, e.g., by designing for maintainability, and through the use of modularity, smart components and systems, and computer based operator aids.

To realize such international co-operations plans need to be developed to retain the existing knowledge and experience, to foster the sharing of science and development activities, and to strengthen multinational structures for education and development. The IAEA has already initiated such activities [4.6-7].

4.6.3. Concluding remarks

The growth of nuclear power will be facilitated by changes in infrastructure. General globalization will foster globalization of nuclear infrastructure. Innovation in nuclear infrastructure arrangements along with changes in economic and market structures in the world could facilitate the deployment of innovative nuclear energy systems. In particular, countries adopting nuclear power could benefit from such global development, since it would not be necessary to develop all elements of the nuclear power infrastructure in each country separately. Such globalization would require enhanced international cooperation to reach agreement on requirements to be met and standards to be used in operating nuclear power facilities.

Technical innovations leading to enhanced performance in economics, sustainability and environment, safety, waste management, and proliferation resistance can facilitate changes in infrastructure. Such innovations together with enhanced international cooperation could well help with the issue of public acceptance. Innovation should ultimately lead to nuclear technology that does not require unique measures for governing nuclear risks.

References to Section 4.6

[4.6-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Choosing the Nuclear Power Option: Factors to be Considered, STI/PUB/1050, IAEA, Vienna (1998).

[4.6-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Programme Planning: An Integrated Approach, IAEA-TECDOC-1259, Vienna (2001).

[4.6-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Communications on Nuclear, Radiation, Transport and Waste Safety: A Practical Handbook, IAEA-TECDOC-1076, Vienna (1999).

[4.6-4] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical, Institutional and Economic Factors Important for Developing a Multinational Radioactive Waste Repository, IAEA-TECDOC-1021, Vienna (1998).

[4.6-5] INTERNATIONAL ATOMIC ENERGY AGENCY, "Assessment of the World Market for Small and Medium Reactors", Introduction of Small and Medium Power Reactors in Developing Countries, IAEA-TECDOC-999, Vienna (1998) 205.

[4.6-6] INTERNATIONAL ATOMIC ENERGY AGENCY, Small and Medium Sized Reactors: Status and Prospects, C&S Papers Series No.14/P, IAEA, Vienna (2002).

[4.6-7] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology Review-Update 2003, Annex 2, Knowledge Management, GOV/2003/9, IAEA, Vienna (2003).

CHAPTER 5
INNOVATIVE NUCLEAR TECHNOLOGY ASSESSMENT – INPRO METHODOLOGY

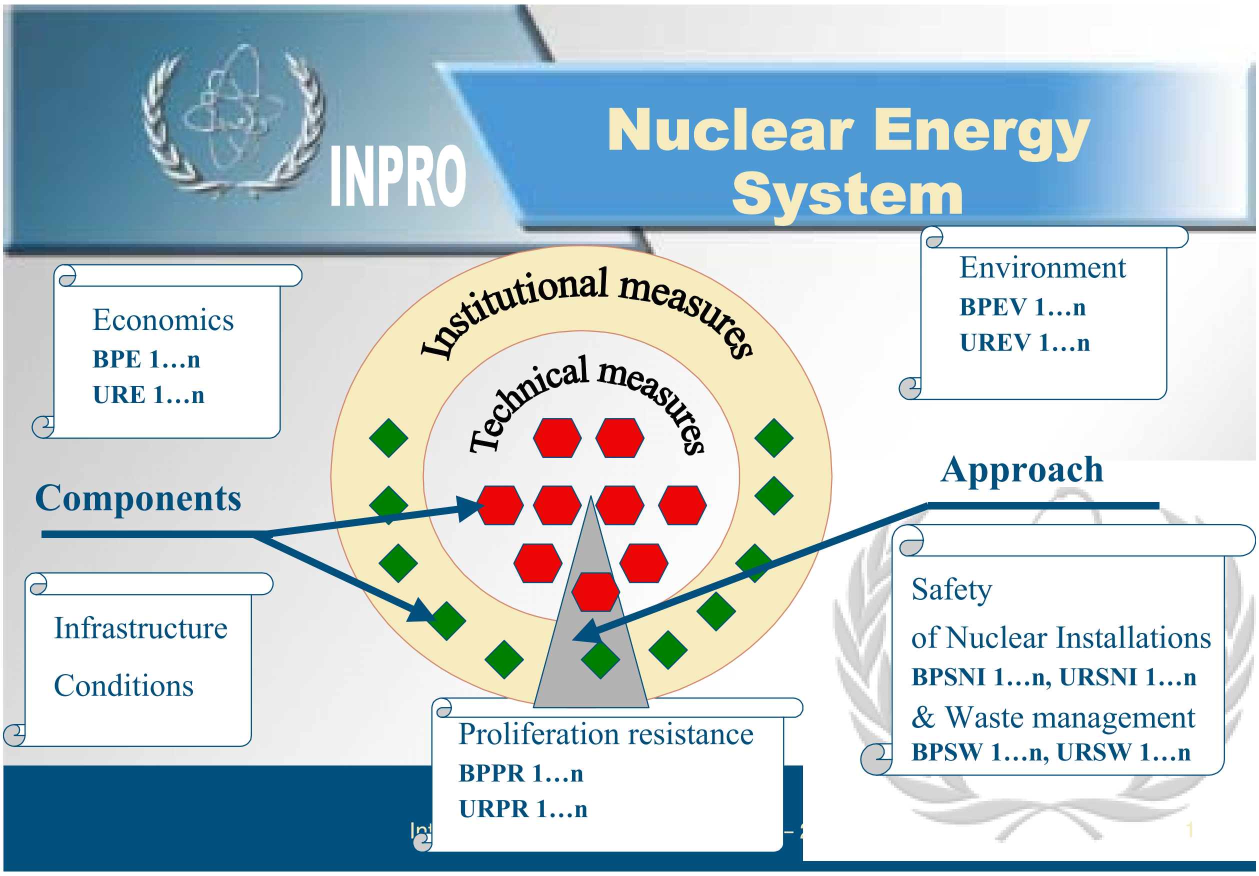
5.1. Introduction

In elaborating national and international recommendations for the large-scale development of innovative nuclear energy systems there is a need for a structured and objective evaluation of options [5-1]. Time and resources are required for the development of innovative energy systems and so care must be taken in the selection of development targets and paths. Errors can be costly and ultimately impact the future viability of nuclear power. In this chapter we set out a methodology, the INPRO Methodology, comprising 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 innovative energy system, or a component of such a system on a national, regional and/or global basis. The methodology presented is based on the results of both a review of existing technology evaluation procedures and on the outcome of several consultancy meetings held by the IAEA. The INPRO Methodology provides Member States with a tool to assist them in identifying and assessing the components, e.g., reactors, waste processing facilities, fuel fabrication and recycling facilities, etc. needed for a future nuclear energy system and the RD&D required to improve existing components for future application and to develop new components as required.

The INPRO Methodology:

- Seeks to make use of the results applicable from similar activities at the international and national levels as far as possible;
- Is oriented more to identifying a range of technology alternatives that will fulfil Basic Principles and User Requirements set out for INS, rather than to selecting a single best solution;
- Recognizes that the methodology will need to be applied iteratively to take into account changes in the requirements and conditions (technical, sociological and economic factors) under which nuclear power will be developed and operated in the future;
- Recognizes that the INPRO User Requirements and Criteria may be supplemented by additional Requirements and Criteria, e.g. taken from existing Standards and Guides; and
- Recognizes that for innovative reactors and fuel cycles additional work is likely required to elaborate requirements and standards.

The basic objective for a Member State (MS) is to evaluate how a proposed INS and associated Approaches (defined in Section 5.2) comply with the Basic Principles, User Requirements and Criteria that have been developed as part of INPRO, Phase 1A, and to present this information in tabular form. A MS may be interested in only a single component of a complete energy system, such as a reactor for electricity production, or an integrated system involving, mining, conversion, enrichment, fuel production, a suite of reactors reprocessing, and P&T. While, in the former case, the reactor technology may be the focus of development by the MS, nonetheless, in assessing this component the MS must also identify the other components (that will be required for the MS to use the reactor, such as fuel



INPRO

Nuclear Energy System

Economics
BPE 1…n
URE 1…n

Environment
BPEV 1…n
UREV 1…n

Institutional measures

Technical measures

Components

Approach

Infrastructure
Conditions

Safety
of Nuclear Installations
BPSNI 1…n, URSNI 1…n
& Waste management
BPSW 1…n, URSW 1…n

Proliferation resistance
BPPR 1…n
URPR 1…n

Fig 5.1. Illustration of INPRO methodology definitions.

production, waste management, etc.) and present information on these components as well as on the specific component of principle interest to the MS, namely the reactor. In this way a holistic view is developed and presented. It is recognized that in addition to the Basic Principles, User Requirements, and Criteria developed by INPRO, Phase 1A, a given MS may use additional requirements (see, for example, Refs [4.3-1, 4.3-2, 4.3-5, 4.3-6, 4.3-8, 4.3-12, 4.3-13, and 5-2]) or, in the course of an assessment, develop additional requirements and associated criteria that need to be taken into account in the assessment. All of these would also be presented for consideration.

It is expected that feedback from using the INPRO methodology will lead to changes in the methodology itself and to the User Requirements, and, in particular, the Criteria that are at the heart of the methodology, and also, possibly, to the Basic Principles.

5.2. Terminology and basic features of the INPRO methodology

The INPRO methodology relies on an assessment of how well an innovative energy system and associated approaches comply with:

- Basic Principles (BP);
- User Requirements (UR); and
- Criteria, each consisting of an Indicator and the Acceptance Limit (C, I and AL);

Definitions of BP, UR and C, I, and AL have been presented in Section 3.

An **Approach** (see Figure 5.1 and Table 5.1) is the method, comprising a set of industrial objects, technical, economical, political and/or other institutional measures and appropriate steps in all relevant areas, that is used to ensure that a given energy system meets the BP and UR. An Approach may depend on national technology development strategies and regional features[29]. Components of an Approach may be at different levels of maturity as discussed below.

Table 5.1. Example of an approach and maturity of components
(the table would be completed by proponents of the innovative energy system)

Approach used in the INS (including enabling technologies and institutional measures). Components of the Approach:	*Maturity Status* of the components of the Approach. (Groups 1,2,3, or 4 reflect technical maturity, see Section 5.2)
Innovative reactor HTR with molten salt cooling.	Conceptual design, thermo hydraulic experiments (Group 3).
Closed fuel cycle with dry reprocessing.	Laboratory experiments (Group 2).
Natural circulation driven core cooling.	Engineering experiment of a limited scale (Group 2).
Coated particle type fuels.	Proven in reactors (Group 1).
Use of international waste disposal park (Institutional measure).	Idea to be explored (Group 4).

The outcome of the assessment is a **Judgment** of the potential of a given component (or of all components) of a nuclear energy system to fulfil a given (or all) User Requirement(s), and finally the potential of an entire nuclear energy system to fulfil a given (or all) Basic Principle(s). The judgment is based on an evaluation of the indicators to decide whether they will be inside or outside the acceptance limits defined in the criteria.

The Judgment value for a proposed INS (or for a component thereof) may be one of the following: **Very High Potential (VHP)**; **High Potential (HP); Potential (P)**; or **No Potential (NP).** The meaning of these terms is set out in Table 5.2.

.

---

[29] The term "regions" may have different meanings including: geographical; economical (analogous to "market segments"); socio-political; technical (preferences and priorities placed on certain types of installations (desalination, district heating, industrial heat, etc.).

Table 5.2. Outcomes of technology assessment against a definite criterion by applying the INPRO methodology

Judgment (The approach of an INS is judged to have).	*Meaning of the Judgment* (The reason for 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 (Possibly satisfying 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.

In assessing a given INS users may discover a need to introduce new criteria (or even requirements). In this case, the following considerations should be taken into account:

- To the extent possible, the Criteria (indicators and acceptance limits) should be common to all Approaches. When there is more than one Approach to meet one UR, several Criteria may need to be established for each Approach;
- Where possible, the Criterion should be prescriptive;
- Criteria should not include prejudgments;
- Wherever possible, indicators should be measurable and quantifiable, as well as logically independent; and
- The Criteria should be sufficient and established in such a way that the fulfilment of all Criteria should ensure that Users are convinced that the User Requirements are met.

An assessment (of how well a nuclear energy system and associated Approaches comply with Basic Principles, User Requirements and Criteria) is a bottoms up process starting with Judgments (VHP, HP, etc.) of the ability to comply with each criterion. A nuclear energy system (and associated Approach(es)) are judged to have a Very High potential (VHP) to satisfy a given User Requirement when it has Very High potential to meet all Criteria linked to this User Requirement. If the Judgment for at least one of the associated requirements is only High (and no criteria are less than High) then the Judgment for this User Requirement is High. Similarly, if the Judgment for one criterion linked to a given Requirement is Potential and no criterion is less than Potential, then the Judgment of meeting this Requirement is only

Potential and if the Judgment of any criteria linked to a given User Requirement is No Potential, then the Judgment for this User Requirement is also No Potential.

A similar logic is applied to the User Requirements associated with a given Basic Principle to determine the Judgment for the Basic Principle.

5.3. Basic procedure of the INPRO methodology

The assessment of a nuclear energy system (or a component thereof) using the INPRO methodology involves the following steps:

- The nuclear energy system to be assessed and its components are specified;
- Approaches for meeting all relevant Criteria, User Requirements and Basic Principles are specified for the nuclear energy system;
- Judgments are established of the potential of the Approaches and their constituent components to meet the Criteria, User Requirements and Basic Principles for the nuclear energy system, and
- A Judgment of the entire system is arrived at from the Judgments on compliance with all of the Basic Principles, User Requirements, and Criteria.

Tables 5.3 and 5.4 illustrate a partial set of information that would be presented to summarize such an assessment. Information of the type presented in Table 5.3 is based on lower level information developed at the early stages of applying the methodology (See Table 5.1).

Table 5.3. Example for stepwise procedure of the INPRO methodology

Area of assessment/Basic Principle (BP)	User requirement (UR)	Criteria		Approach	Judgment on the Approach
		Indicator	Acceptance limit		
1. Economy (E) BPE 1 *The cost of energy from innovative nuclear energy systems… must be competitive with that of alternative energy sources* ….BPE n	URE 1.1 *All life-cycle costs included in the energy system shall be accounted for and the cost of nuclear generated energy, C_N, shall be competitive with that of alternate energy sources*, C_A. URE 1.2….URE n: URE n….	IE 1.1.1 Cost of nuclear energy, C_N IE 1.1.2…IE 1.1.n IE 1.2.1…IE 1.2. …..	ALE 1.1.1 $C_N < kC_A$ ALE 1.1.2…ALE 1.1.n		Very high potential (VHP) or: High Potential (HP) or: Potential (P) or No Potentials (NP)
2. Environment (EV) BPEV 1 *The expected (best estimate) adverse environmental effects of the nuclear energy system must be well within the performance envelope of current nuclear energy systems delivering similar energy products.* BPEV n	UREV 1.1 *The environmental stressors from each part of the system over the complete life cycle must be controllable to levels meeting or superior to current standards*	IEV 1.1 L_{St-i}, level of stressor i	ALEV 1.1.1 $L_{St-i} \leq S_i$, where S_i is the standard for stressor i		VHP or: HP or: P or NP

Table 5.3. Example for stepwise procedure of the INPRO methodology (cont.)

3. Safety of nuclear installations (SNI) *BPSNI 1* *Innovative nuclear reactors and fuel cycle installations shall incorporate enhanced defence-in-depth ...and the levels of protection... shall be more independent from each other than in current installations.* ….BPCNI n	URSNI 1.1: *Innovative nuclear reactors and fuel cycle installations should be more robust relative to existing designs regarding system and component failures as well as operation.* *URSNI.2….URSNI1.n*:	ISNI 1.1.1: Robustness of design (simplicity, margins). ISNI 1.1.2…ISNI 1.1.n	ALSNI 1.1.1: Superior to existing designs. ALSNI 1.1.2…ALSNI 1.1.n		*VHP* *HP*
4. Waste management (W) *BPW1:* *Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.* *BPW2…BPWn*	*URW 1.1 Intermediate steps between generation of waste and the end state should be taken as early as reasonably practicable.* *URW 1.2…URW1.n*	IW 1.1.1 Time to produce waste form as specified for the end state. IW1.1.2.I IW.1.1.n	ALW 1.1.1 As short as reasonably practicable. ALW 1.1.2…ALW 1.1.n		
5. Proliferation Resistance (PR) *BPPR1 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* BPPR n	URPR1.1 *Proliferation resistance features and measures should ..help ensure that future nuclear energy systems will continue to be an unattractive means to acquire fissile material for a nuclear weapons program.* URPR 1.2 …URPR1.n	IPR 1.1.1 Confidence that the proliferation resistance features … help to ensure that the INS is an unattractive means to acquire fissile material for a nuclear weapons program. IPR 1.1.2..IPR1.1.n	ALPR 1.1.1 An acceptable rating on a qualitative scale ranging from unacceptable to outstanding. ALPR1.1.2…ALPR 1.1.n		VHP HP
	Other, e.g., Regional Requirements				

Table 5.4. Technology evaluation scheme: Description of specific requirements of the Member States and their judgments on a given design concept (To be filled by INPRO task groups and by Member States)

Region (market segment being addressed): ______________________________

Name of integrated nuclear system concept: ______________________________

Basic Principles in 5 areas: 1.Economics, 2. Environment. 3 Safety of reactors and fuel cycles, 4. Safety of waste management, 5. Proliferation resistance	INPRO User Requirements (A)	Indicator (B)	Acceptance limit suggested by INPRO (C)	Acceptance limit acceptable by Member State (D)	Expected achievable value estimated by proponents for that indicator (E)	Judgment: Potential of the concept to meet:		Basis for Judgement
						(D)*	(A)	
3. Safety Nuclear Installations (SNI) *BPSNI 2* *The innovative nuclear reactors and fuel cycle installations shall prevent, reduce or contain releases …to the point that these risks are comparable to that of industrial facilities used for similar purposes.*	*URSNI 2.1. Innovative reactors and fuel cycle installations should meet dose limits accepted world wide as defined by the International Commission on Radiological Protection (ICRP).* *URSNI 2.2… URSFR 2.n*	*ISNI 2.2.1* *Dose value* *ISNI 2.2.2..2.2.n*	*ALSNI 2.2.1* *Less than ICRP limits* *ALSNI 2.2.2…* *ALSFR 2.2.n*	*ALSNI 2.2.1* *ALSNI 2.2.2…* *ALSNI 2.2.n*		*VHP or* *HP or* *P or NP* *Against* *URSFR 2.1 Against URSNI 2.2…2.n*	*Against BPSNI 2*	
	Other requirements							

[*] Methods used for the evaluation of compliance with the Criterion (C), (D) See Section 5.5.

Additional factors will also enter into any assessment including the **maturity status** of the nuclear reactor and fuel cycle technologies. As a step in the INPRO methodology, each technology should be classified into the appropriate category defined below. 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.

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.

In assessing INS against Basic Principles, User Requirements, and Criteria, existing technologies and plans for their evolutionary development will be assessed with existing operational experience and achieved results taken into account. In any comparison of existing/evolutionary systems with innovative systems the maturity of the Approaches – a priori higher for existing technologies – should not influence negatively the judgment of the assessment of a future technology with respect to its potential for meeting the Requirements. Correctly formulated and used, the INPRO Methodology, with its Principles, Requirements and Criteria, should be viewed as a facilitator for development rather than a tool for unfair screening or a discriminating mechanism for technologies of as yet unproven worth. In this context the basis for the Judgement arrived at needs to be explicitly laid out (See section 5.5). The basis for the judgment will be influenced by the maturity of the technology.

5.4. Applications of the INPRO methodology and future developments

If the INPRO Methodology is to become a useful assessment tool it will be necessary to develop, in due course, support tools such as User Manuals, Guidelines etc. Prior to undertaking such a task the usefulness of the methodology needs to be assessed by applying it to a number of Case Studies (Section 5.5).

To date, INPRO has developed a broad set of Basic Principles, User Requirements, and Criteria that are seen to be applicable generally to all innovative energy systems. But within a given MS it is expected that additional requirements and, especially, criteria, related to specific features of the systems under study and national and regional specificities, priorities, and constraints will be identified. For a given assessment such requirements and criteria will need to be assembled and combined with the INPRO requirements to form one set of comprehensive requirements.

In general, an assessment should focus on finding nuclear energy systems (including technology options and institutional measures) able to satisfy the Basic Principles and User Requirements defined by INPRO. It can be expected that for future nuclear energy systems a number of different nuclear technology concepts might be needed to meet the differing preferences of various regions. Approaches to meeting User Requirements will need to specify enabling technologies and components required to define a comprehensive nuclear energy system for assessment. It is desirable to have common Indicators and Acceptance Limits (Criteria) for different Approaches. Nevertheless, for some energy system concepts and associated Approaches different technical Criteria may be needed.

It is unlikely that a single technology option or nuclear system will meet all User Requirements in the different areas (economics, environment, safety, waste management, and proliferation resistance) covered by INPRO. Some possible ways for improving technical characteristics of nuclear energy systems and the corresponding enabling technologies have been already identified [5-3], and it may be expected that more than a number of concepts of future nuclear energy technologies will play a role in meeting the INPRO Basic Principles and User Requirements [5-4, 5-5].

In the nuclear reactor sector, the technical criteria and specifications for PWRs, BWRs, HWRs and AGRs are based on more detailed studies compared to those for FRs and HTGRs. The requirements and criteria for the former group of reactors are perfectly adequate for the purposes of comparing existing power reactors; however, when dealing with evolutionary and innovative designs they can serve only as an example for the development of new standards, using the INPRO Basic Principles, Users' Requirement, and Criteria as a starting point. As the INPRO methodology is applied, Basic Principles, User Requirements, and Criteria will be subject to periodic review and will almost certainly be modified in the light of experience.

As a first step in testing the INPRO Methodology by applying it, INPRO Member States are requested to put forward their recommendations for case studies to be done on prospective innovative energy systems using the Methodology. Case studies are discussed in the next section.

5.5. Case studies

5.5.1. Objective

Case studies are to be performed to gain experience with the INPRO methodology (INPRO BP, UR, Criteria, augmented as necessary with case specific UR, and the assessment formalism set out in Sections 5.2 and 5.3) to obtain experience with the methodology and to assess, at a minimum, the following:

- Whether the INPRO Basic Principles, User Requirements and Criteria (indicators and acceptance limits) are understandable, workable, consistent (avoid redundancy), comprehensive (are additional URs and Criteria needed?), and dependent or independent of the system studied; and

- 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 innovative energy system.

It is envisioned that case studies will be performed by individual interested Member States supported by Task groups with broader participation of experts from INPRO Member States.

5.5.2. Requirements for performing a case study

The nuclear energy system proposed for a case study must comprise an entire system (reactor and complete fuel cycle, including its infrastructure and institutional measures), encompass the complete life cycle from design to decommissioning, and there must be a reasonable expectation that it could be deployed within the next 50 years, taking into the account the RD&D required. Ideally, to test the methodology, case studies should be carried out for different types of nuclear energy systems, such as:

- A global system with components at the preliminary stage of development;

- A future system that is already reasonably well developed; and

- Systems being considered for application in different regions.

The case study shall not consider only the technology, but must also include the institutional and/or regional features and one or more Approaches (see section 5.2).

The outcome of the case study will represent a preliminary assessment of the suggested technology or nuclear energy design concept. It will represent the views of the participants in the assessment process, rather than the position of the IAEA or all INPRO Member States.

Some MS may already have case studies in mind. MS that are interested in performing a case study but who do not have a specific system in mind may wish to make use of Ref. [5-6] to assist them in formulating their case study.

5.5.3. Deliverables

The case study will be documented in a report that presents a description of the system studied, including the following:

- The regional context in which the system is to be deployed;
- A global assessment of the methodology against the objectives set out above, which identifies strengths, weaknesses and makes recommendations for further work;
- An evaluation of each of the BP, UR and the associated criteria, including their:
  - Ease of use,
  - Completeness of the BP, UR, and Criteria, and suitability of the acceptance limits,
  - Meaningfulness of the results,
  - Discriminative power,

- – The adequacy to take into account system and regional specificities (without adaptation),
  - – Modifications required to adapt the BP, UR, and Criteria to the system and to the regional specificities,
  - – Usefulness in assessing the system, comparing systems, identifying gaps, showstoppers, and requirements for future work,
  - – Recommendations to retain, modify, delete, or add Basic Principles, User Requirements, and Criteria (indicators and acceptance limits), and
  - – Assessment of uncertainties related to the analysis of the innovative energy systems and of the impact of uncertainties in information used in the case study; and
- The Judgments and the bases for the Judgments arrived at concerning compliance with the BPs, URs and Criteria.

5.6. Basis for judgments

In making a Judgment of the potential to comply with a given Criterion and hence with the User Requirements and Basic Principles, the rationale for arriving at that Judgment, i.e. the basis of the Judgment, needs to be developed and explained. The basis may include preliminary or detailed safety and environmental analyses carried out using the methods set out, e.g., in sections 4.3 and 4.2. Judgements may also be based in whole or in part on experience with large-scale test facilities or experimental test rigs, on extrapolation of experience from similar facilities, or on engineering judgment and combination of these. For innovative facilities without an extended experience base, i.e. the fourth category (conceptual technologies), expert opinion will be very important in forming the Judgment. In such cases an explanation should be given of the qualifications and experience of the experts who participated in forming the expert opinion and of any special techniques/procedures, e.g., Delphi, that were employed to arrive at the opinion.

5.7. Concluding remarks

- The basic terminology and technique for implementing the INPRO Methodology for the assessment of INS, including the formats for the presentation of information, have been developed and the methodology is now at a stage where it can be applied on a trial basis**;**

- Substantial effort will be needed to develop the methodology further for widespread use and to ensure consistency and credibility of the results. Prior to committing to such an effort, an assessment of the efficacy of the methodology should be obtained by using it in a number of case studies; and

- Improvements to the Methodology are expected to result from such case studies and further applications in Phase 1B of INPRO.

References to Chapter 5

[5-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Enhanced Electricity System Analysis for Decision Making – A Reference Book, Decades project document No. 4, IAEA, Vienna (2000**).**

[5-2] BERBEY, P., “European Utility Requirements: Actions in Progress and next steps”, international Congress on Advances in Nuclear Power Plants, ICAPP 03, May 4-7 2003, Cordoba, Spain.

[5-3] THE RUSSIAN RESEARCH CENTER ‘KURCHATOV INSTITUTE’, International Project “Power Provision of Mankind’s Sustainable Development, Cardinal Solution of the Nuclear Weapons Non-Proliferation Problem, and the Problem of the Environmental Recovery of the Earth Planet” Preprint RRC Kurchatov Institute, IAE-6213/3, Moscow (2001).

[5-4] CARRE, F., “CEA Rethinking the Nuclear fuel Cycle”, International Symposium on the Role of Nuclear Energy in Sustainable Development, 19-20, April 2001. Cambridge, Massachusetts, USA.

[5-5] OECD NUCLEAR ENERGY AGENCY, Nuclear energy in a sustainable development perspective, OECD/NEA, Paris (2000).

[5-6] OECD INTERNATIONAL ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL NUCLEAR ENERGY AGENCY, Innovative Nuclear Reactor Development Opportunities for International Cooperation, OECD/IEA, Paris (2002).

CHAPTER 6
CONCLUSIONS AND RECOMMENDATION

This report brings Phase 1A of INPRO to a conclusion. Phase 1A is 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, nuclear "haves" and "have-nots", and developing and developed countries to jointly consider actions needed to accelerate nuclear innovation in directions most likely to be most useful to the energy markets of the future.

Phase 1A has reviewed expected energy needs in the 21st century, and the potential role of nuclear energy, using scenarios from the Special Report on Emission Scenarios by the Intergovernmental Panel on Climate Change. SRES clearly shows that energy demand, and especially electricity demand, will grow substantially regardless of which mix of driving forces ends up dominating future world developments. Moreover, nuclear energy plays a significant role in nearly all the 40 SRES scenarios, including the four analyzed in this report. This contrasts with near-term projections by the IAEA, OECD-IEA and US DOE Energy Information Administration that show a declining nuclear share in global electricity production in coming decades, and little or no nuclear movement into energy applications beyond electricity. The difference between these more pessimistic near-term projections and a truly substantial future contribution of nuclear energy – one that takes nuclear's percentage of the world's primary energy supply well beyond today's single digits to 20%, 50% or more – is innovation. The pathway to this future is innovative nuclear energy systems.

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 of the calibre and size needed to support a truly substantial nuclear contribution to global energy supplies.

To help co-ordinate and guide the development of innovative nuclear energy systems, INPRO Phase 1A has set out initial Basic Principles, User Requirements and corresponding Criteria in the areas of economics, the 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 innovative nuclear energy systems 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. All these outputs, from basic principles to the INPRO assessment methodology, are expected to be steadily sharpened and adjusted based on feedback from early applications and case studies.

Specific recommendations for the future are 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 1B of INPRO, Member States define in further detail the RD&D initiatives set out in the report and set out priorities. The IAEA could provide valuable assistance in facilitating co-operation among Member States and establishing complementary co-ordinated research projects;

- Case studies be encouraged to enable Member States and independent analysts to assess prospective innovative nuclear energy systems using the INPRO methodology; and

- Feedback and experience from case studies and other applications be used to sharpen and adjust the INPRO Basic Principles, User Requirements, Criteria and Methodology to continually improve their usefulness.

ABBREVIATIONS

ADS	accelerator driven system
AGR	advanced gas reactor
ALARA	as low as reasonable achievable, social and economic factors taken into account
ALARP	as low as reasonable practical, social and economic factors taken into account
BP	basic principle (INPRO)
CFE	cost free expert (INPRO)
BWR	boiling water reactor
EUR	European utility requirements
FP	fission products
FR	fast reactor
GC	IAEA General Conference
GHG	green house gas
GIF	Generation IV International Forum
HLW	high level waste
HTGR	high temperature gas reactor
HWR	heavy water reactor
I&C	instrumentation and control
IIASA	International Institute for Applied System Analysis
IEA	International Energy Agency
ICG	International Co-ordinating Group in INPRO
ICRP	International Commission on Radiological Protection
IGCC	integrated gasification combined cycle (coal power plant)
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	innovative nuclear energy system
INSAG	International Nuclear Safety Advisory Group (IAEA)
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
LCA	life cycle assessment
LCI	life cycle inventory
LWR	light water reactor
MFA	material flow assessment
MS	Member States
NEA	Nuclear Energy Agency (Paris)

NGO	non-governmental organization
NPP	nuclear power plant
NPV	net present value
NRC	Nuclear Regulatory Commission (USA)
OECD	Organisation for Economic Co-operation and Development
OECD-90	SRES region of all countries belonging to OECD as of 1990
O&M	operation and maintenance
P&T	partitioning and transmutation
PHWR	pressurized heavy water reactor
PSA	probabilistic safety analysis
PRIS	Power Reactor Information System (IAEA)
PWR	pressurized water reactor
RBMK	graphite moderated fuel channel reactor
RD&D	research, development and demonstration
REF	SRES region of countries with economic reform (formerly eastern Europe and Soviet Union)
RES	Resolution (of the IAEA General Conference)
ROW	SRES region of rest of the world (beside OECD-90, Asia and REF)
SRES	special report on emission scenarios
TOR	terms of reference
UNFCCC	United Nation Framework Convention on Climate Change
UR	user requirement (INPRO)
WANO	World Association of Nuclear Operators
WNA	World Nuclear Association
WIPP	Waste Isolation Pilot Plant (US)
WWER	water cooled water moderated power reactor

LIST OF PARTICIPANTS

Section 1 (Background): P. Friedmann (IAEA), P. Gowin (IAEA), C. Allan (Canada)

Section 2 (Prospects and Potentials): H. Rogner (IAEA, INPRO Task Leader), A. McDonald (IAEA), L. Langlois (IAEA), I. Vera (IAEA), A. Hagemann (IAEA).

Section 4.1 (Economics): H. Rogner (IAEA, INPRO Task Leader), A. McDonald (IAEA), P.Florido (Argentina), C. Allan (Canada), G. Aslanian (Russian Federation), C. Xerri (France), R.K. Sinha (India)

Section 4.2 (Sustainability and Environment): A. Bonne (IAEA, INPRO Task Leader), M. Gray (IAEA), O. Azpitarte (IAEA), E. Falck (IAEA), Y. Bussurin (IAEA), M. Bell (IAEA), M. Carreter (IAEA), G. Collard (Belgium), H. Wider (EC), K.L. Sjoblom (Finland), I. Ossipiants (Russian Federation), M.J. Song (Republic of Korea), J.L. Gonzalez (Spain), R. Uzmen (Turkey), E. Knoglinger (Austria:), K. Dormuth (Canada, Chairperson), A. Selling (Netherlands), V. Kuznetsov (Russian Federation), A. Monzo (Spain), R. Dones (Switzerland), V. Averkiev (Russian Federation), J.M. Hallemanns (France), C. Xerri (France).

Section 4.3. (Safety of Nuclear Installations): P.E. Juhn (IAEA, INPRO Task Leader), A. Carnino (IAEA, INPRO Task Leader), V.G. Snell (Canada, Chairperson), E.F. Hicken (Germany, Chairperson), S.H. Chang (Republic of Korea), P.N. Alekseev and P.A. Fomichenko (Russian Federation), M.T. Dominguez (Spain), S. Shikakura (Japan), A. Birkhofer (Germany), A.Y. Gagarinski (Russian Federation), E.G. Kudryavtsev (Russian Federation), V.A. Sidorenko (Russian Federation), W. Thomas (Germany), B. Kuczera (IAEA), K. Fukuda (IAEA), M. Gasparini (IAEA), Y. Bussurin (IAEA), D. Saha (IAEA), P. Nocture (IAEA), P. Friedmann (IAEA), G. Dyck (Canada), C. Ganguly (India), G. Uchiyama (Japan), K.S. Chun (Republic of Korea), D. Greneche (France), Y. Bibilashvili (Russian Federation), G. Sabundjian (IAEA), H. Weidinger (Germany), H. Wider (EC).

Section 4.4 (Waste Management): P.E. Juhn (IAEA, INPRO Task Leader), M. Bell (IAEA), K. Dormuth (Canada, Chairperson), E.Knoglinger (IAEA), M. Gray (IAEA), Y. Bussurin (IAEA), G.T Oviedo (Chile), M.D. Greneche (France), N.K. Bansal (India), K.S. Chun (Republic of Korea), A. Erastov (Russian Federation), L. Soukhanov (Russian Federation), A. Boelme (Turkey).

Section 4.5 (Proliferation Resistance): D. Hurt (IAEA, INPRO Task Leader), K.M. Choi (IAEA), R. Nishimura (Canada, Chairperson), T. Shea (IAEA), J. Lodding (IAEA), V. Kagramanyan (IAEA), Z. Liu (IAEA), C. Xerri (France), G. Pshakin (Russian Federation), P. Florido (Argentina), A. Schaper (Germany), W.I. Ko (Republic of Korea), K.B. Oh (Republic of Korea), K. Mayer (EU), J.S. Lee (IAEA), W. Gmelin (IAEA), L. Vinhas (Brazil), A. Laidlaw (Canada), M. Albert (France), V. Kuznetsov (Russian Federation), D. Toltchenkov (Russian Federation), G. Stein (Germany), R. Versluis (USA), A. Burkart (USA), S. Mcguire (USA), M. Martellini (Italy), A. Lantieri (Italy), L. Rockwood (IAEA), Y. Bussurin (IAEA), R. Cirimello (Argentina), D. Greneche (France).

Section 4.6 (Crosscutting Issues): Y. Yanev (IAEA, INPRO Task Leader), B. Gueorgiev (IAEA, INPRO Task Leader), R. Steur (IAEA), C. Allan (Canada), R. Mahadeva (IAEA), W. Shen (IAEA), H. Rogner (IAEA), L.M. Langlois (IAEA), F.C. Rey (Argentina), A. Gagarinski (Russian Federation), I. Facer (United Kingdom), P. D’Hondt (Belgium),

J. Remacle (Belgium), D. Tregunno (Canada), X. Fang (China), J. Kralovec (Czech Republic), V. Averkiev (Russian Federation) , A. Gagarinski (Russian Federation), D. Kovchegin (Russian Federation), V. Orlov (Russian Federation), I. Parzer (Slovenia), A. Stritar (Slovenia), M. Malave (Spain), M. Casero (Spain), H. Wider (EC), N. Pelzer (Germany).

Section 5 (Methodology for Assessment): V. Kagramanyan (IAEA, INPRO Task Leader), M. Khorochev (IAEA), B. Kuczera (IAEA), P. Friedmann (IAEA), S. Hirschberg (Switzerland), S. Subbotin (Russian Federation), A. Garmash (IAEA), Y. Bussurin (IAEA), R.K. Sinha (India), M. Gray (IAEA), V. Snell (Canada), H. Wider (EC), R. Steur (IAEA), J. Vergara (Chile), G.L. Fiorini (France), J.A.D. Dieguez (Brasil), A. Boelme (Turkey), P. Florido (IAEA), E. Hicken (Germany, Chairperson), C. Xerri (France), G. Aslanian (Russian Federation), H. Weidinger (Germany), F. Depisch (Germany), C. Allan (Canada), E. Knoglinger (IAEA).